A Critical Appraisal of Isokinetic Knee Flexor-Extensor Strength Profiling in Elite Soccer Players

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Abstract

Epidemiological research has identified thigh musculature and knee ligament injuries are of most concern in professional soccer. With strength identified as a modifiable risk factor, isokinetic dynamometry has become a popular means of injury screening. However, isokinetic assessments are criticised based on their lack of functional relevance to injury aetiology. Study one describes isokinetic screening of the thigh musculature in an elite cohort of male soccer players assessed at 60, 180 and 270$^{o} \cdot s^{-1}$ across four knee joint angles (70-40°). This study identified strength characteristics were velocity and angle dependent, advocating the use of novel metrics and a range of angular velocities for future isokinetic screening. Study two identified these procedures of assessment were modifiable during late stage rehabilitation of an elite soccer player. When considering the influence of gender and age on lower limb injury incidence, studies three and four identified the proposed isokinetic procedures were sensitive to differences in playing age between male and female youth and adult soccer players. In addition to isokinetic assessments, kinematic analysis of functional movements were completed. Study five comprised kinematic (sagittal and frontal planes) assessment of single leg hop and change of direction tasks performed using sidestep and crossover techniques with female soccer players. When considering previous criticisms of isokinetic testing not being functionally relevant, the knee angles and angular velocities identified in study five were used to predict knee flexor and extensor torque expressed by knee joint angle and velocity (study six). Study seven compared the predicted strength values to the knee joint moments exhibited during the hopping tasks. Strength assessments should use joint angle and velocity to profile musculature strength with increased functional relevance, and may identify additional training needs. These studies also allow strength profiling during the completion of functional tasks that may inform increasingly specific interventions.

Key words: Injury, Screening, Isokinetic Dynamometry, Soccer, Playing Age, Gender

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List of Abbreviations and Acronyms

ACL	Anterior cruciate ligament
APT	Angle of peak torque
AST	Angle-specific torque
CI	Confidence intervals
conKE	Concentric knee extensor
DCR	Dynamic control ratio
DCR_{AST}	Angle-specific dynamic control ratio
eccKF	Eccentric knee flexor
FR	Functional range
GLM	General linear model
Hz	Hertz
ICC	Interclass correlation coefficient
KE	Knee extensor
KF	Knee flexor
MCL	Medio collateral ligament
N	Newtons
Nm	Newton metres
PT	Peak torque
QTM	Qualisys track manager
R^2	R squared
SD	Standard deviation
SEM	Standard error of measure
W	Watts
η^2	Partial eta squared
^{o}	Degrees
$^o \cdot s^{-1}$	Degrees per second
m/s	Metres per second

CHAPTER 1

Introduction

1.1 Overview

The epidemiology and aetiology of injury in association football (soccer) has been well documented (LeGall et al. 2006, 2008; Hartmut et al. 2008; Ekstrand et al. 2011; Ekstrand et al. 2013; Hägglund et al. 2013; Waldén et al. 2013; Ekstrand et al. 2016; Renshaw and Goodwin, 2016). Previous observations have identified that knee flexor and anterior cruciate ligament (ACL) injuries are of most concern due to the high incidence and severity of these injuries, respectively (Brophy et al. 2012; Waldén et al. 2011; Ekstrand et al. 2011; Ekstrand et al. 2013; Hägglund and Waldén, 2015; Bahr, Clarsen and Ekstrand, 2017). However, previous research concerning injury risk has primarily focused on senior aged male soccer players (Ekstrand et al. 2013; Hägglund et al. 2013; Waldén et al. 2013; Ekstrand et al. 2016), despite youth and female soccer players are also predisposed to knee flexor and ACL injuries (LeGall et al 2006, 2008; Hartmut et al. 2008; Ekstrand et al. 2011). Furthermore, female soccer players are predisposed to a greater number of ACL injuries when compared to males (LeGall et al. 2008; Harmut et al. 2008; Waldén et al. 2011) which is increasingly prevalent in youth female soccer players aged 15-19 years (Renstrom et al. 2008; Hägglund and Waldén, 2015). Despite the large body of research and advancements made in sport science, there has been no decline in the incidence of thigh musculature and knee ligament injuries in senior aged professional male soccer players (Ekstrand et al. 2013; Waldén et al. 2015). These observations may also be consistent for youths and female soccer players, thus there appears a need to further develop screening methods that are designed to inform exercise prescription for the reduction of potential injury risk.

Knee flexor (KF) and knee extensor (KE) strength has been identified as a modifiable risk factor for thigh musculature and knee ligament injuries, with strength deficits and imbalances being associated with injury risk (Askling et al. 2003; Croisier et al. 2008; Fousekis et al. 2011; Petersen et al. 2011; van der Horst et al. 2015; Augustsson and Ageberg, 2017; Attar et al. 2017; Lee et al. 2017). Strength characteristics of KF and KE are commonly assessed and determined using isokinetic dynamometry in soccer players (Dauty et al. 2003; Zakas, 2006; Fousekis, Tsepsis and Vagenas, 2010; Fousekis et al. 2011; Jenkins et al. 2012; Manson et al. 2014) and considered as the criterion measure for muscular strength (Stark et al. 2011). However, previous prospective studies have yielded equivocal in senior aged male soccer players for predicting KF injuries (Croisier et al. 2008; Lee et al. 2017; Van Dyk et al. 2016, 2017; Bakken et al. 2018) and may be attributed by the methods used to characterise strength (El-Ashker et al. 2015; De Ste Croix et al. 2017).

Injury risk in soccer is associated with movements that place large mechanical demands upon the lower limbs (Proske et al. 2004; Bloomfield et al. 2007; Small et al. 2010). With specific reference to the KF, previous observations have identified that high-intensity running and sprinting tasks are associated with increased injury risk to these musculature (Hawkins and Fuller, 1999; Woods et al. 2004; Malone et al. 2018). Furthermore, deceleration, landing and change of direction tasks are associated with increased knee ligament injury risk (Hewett et al. 2005; Kristianslund and Krosshaug, 2013; Fox et al. 2017; Leppänen et al. 2017). The completion of the aforementioned tasks also exhibit increased knee extension angles and velocities (Kivi, Maraj and Gervais, 2002; Wang, 2011; Nedergaard et al. 2014), thus It can be suggested that these movements should inform methods used to characterise isokinetic strength of the KF and KE in relation to injury risk. Specifically, determining precise knee joint angles and velocities exhibited during biomechanical assessments of functional tasks may consequently be used to inform and assess strength of the KF and KE. Such considerations may enhance the specificity of strength assessments that are informed by quantifying thigh musculature strength values during the completion of movements associated with KF and ACL injuries in soccer players. Consequently, this may also identify if the thigh musculature are disproportionate to the moments placed upon the knee joint, and may have implications for increased injury risk (Shimokochi et al. 2009; Podraza and White, 2010; Hewett et al. 2010; Leppänen et al. 2017). These considerations may also determine strength discrepancies of the thigh musculatures where KF and ACL injuries are suggested to occur (Boden and Dean, 2000; Olsen et al. 2004; Chumanov et al. 2012; Higashihara et al. 2015).

1.2 Thesis Aims and Structure

The thesis comprises seven experimental studies, presented across two Sections. Section A has a focus in the critical examination of isokinetic dynamometry in assessing eccentric KF (eccKF) and concentric KE (conKE) strength. At the outset of the PhD, contemporary isokinetic dynamometry analysis was typically summarised as peak torque, and associated strength ratios (Van Dyk et al. 2016, 2017; Bakken et al. 2018). Although these metrics determine absolute strength and imbalances of the thigh musculature, peak torque for the KF and KE occur at different knee joint angles (Cohen et al. 2015; El-Ashker et al. 2015; De Ste Croix et al. 2017), and does not characterise strength where injury risk is increased (Boden and Dean, 2000; Olsen et al. 2004; Chumanov et al. 2012; Higashihara et al. 2015). Furthermore, procedures associated with isokinetic dynamometry have commonly adopted low testing velocities to characterise thigh musculature strength, particularly in the assessment of eccKF, despite KF and ACL injury risk being increased at higher angular velocities (Kivi, Maraj and Gervais, 2002; Wang, 2011; Nedergaard et al. 2014).

The first study of the thesis is concerned with the procedures and analytical approaches used to assess bilateral isokinetic strength characteristics of eccKF and conKE in senior aged professional male soccer players across a variety of knee joint angles and velocities. These procedures subsequently determined the late stage ACL rehabilitation responses in a male soccer player across a variety of knee joint angles and velocities from the same cohort of players. The control group were used to approximate a return-to-play baseline, and identify the modifiable nature of thigh musculature strength, relative to knee joint angle and velocity. Since youth soccer players are also predisposed to an increased injury risk when compared to senior aged players (Hewett et al. 2004, 2015; Van Der Sluis et al. 2014, 2015), youths may possess different strength characteristics of the thigh musculature (Gür et al. 1999; Kellis et al. 2001). Furthermore, female soccer players are also predisposed to KF injuries (LeGall et al. 2008; Harmut et al. 2008), in particular to ACL injuries (Renstrom et al. 2008; Waldén et al. 2011; Hägglund and Waldén, 2015), thus these cohorts of players may also display different strength characteristics of the thigh musculature that may influence injury risk. Therefore, Section A of the thesis is also concerned in comparing the defined isokinetic strength metrics of the eccKF and conKE in soccer players with pronounced differences in training history and exposure. These studies are concerned with identifying thigh musculature strength characteristics between senior and youth soccer players, relative to gender and lower limb, with implications for injury risk.

The following section of the thesis comprises of three experimental studies that are designed to investigate the potential to inform further methods of determining thigh musculature strength. These studies are designed to provide greater functional relevance for assessing thigh musculature strength relative to the common mechanisms of injury. Given the exacerbated risk of ACL injuries in senior and youth female soccer players (Renstrom et al. 2008; Waldén et al. 2011; Hägglund and Waldén, 2015), section B of the thesis focuses on these cohorts of players. Section B of the thesis initially presents a kinematic analysis of functionally relevant movements associated with injury between senior and youth female soccer players. This kinematic analysis focuses on knee joint angles and angular velocities that were subsequently used to inform further methods of determining thigh musculature strength, relative to playing age of the female soccer player. The knee joint angles and velocities exhibited during the completion of these functional tasks were used to quantify thigh musculature strength values and subsequently compared between female soccer playing age. Thereafter, these strength values were compared against the knee joint moments exhibited during the completion of these tasks to identify if the thigh musculature are sufficiently developed to dissipate these large forces, relative to female soccer playing age.

Although previous literature has commonly quantified the strength characteristics of the thigh musculature in elite soccer populations, these studies do not appropriately consider the influence of joint angle and velocity on isokinetic strength metrics. These approaches may be more appropriate for characterising thigh musculature strength in elite cohorts of soccer players by quantifying strength metrics at knee joint angles and velocities associated with injury. Such contemporary approaches in isokinetic strength assessments have not been previously explored in professional cohorts of soccer players, and warrants further research. The associated metrics may be modifiable during an appropriate training stimulus in an injured population, and identify additional strength training needs of youth soccer players when compared to adults, relative to gender. Moreover, determining thigh musculature strength at relevant knee joint angles and velocities may subsequently be used to quantify thigh musculature strength during the completion of functional tasks. In turn, these procedures may help practitioners to identify specific player training needs and subsequently inform exercise prescription that may aid the reduction of potential injury risk. The overall aim of the thesis is to further develop the procedures and analytical approaches of determining thigh musculature strength in elite cohorts of soccer players.

CHAPTER 2

Review of Literature

2.1 Introduction

The aims of the literature review are to identify incidence, severity, and risk factors associated with thigh musculature and knee ligament injuries in elite soccer players, and how considering specific injury aetiology can inform design of screening methods. The first section (Section 2.2) of the literature review highlights different injury prevention frameworks detailing how and where the thesis is placed in reference to these models. Section 2.3 identifies the epidemiology of soccer injuries that is specifically concerned with incidence and severity. Thereafter, Section 2.2 discusses the mechanisms associated with KF and ACL injuries to inform critical discussion of common screening methods. Section 2.4 will review the non-modifiable and modifiable risk factors of injury. Specifically, previous injury is a non-modifiable risk factor that is associated with increased future injury risk, and highlights the need to prevent primary injuries. Age and gender are also primary non-modifiable risk factors for injury, and have particular implications for injury risk in soccer due to the professionalisms of these groups of players. Strength is a primary modifiable risk factor for injury that is influenced by playing age and gender, and commonly characterised using isokinetic dynamometry. Knee biomechanics is also a modifiable risk factor for injury, and influenced by playing age and gender. Therefore, Section 2.5 considers how assessments of thigh musculature strength and knee biomechanics should be specific to the mechanisms associated with injury.

2.2 Summary of Injury Prevention Frameworks

Injury risk screening in sport is commonly conducted to identify individuals who may or may not present signs or symptoms associated with specific injuries (Bahr, 2016). Screening for injury risk in sport forms an integral aspect of injury prevention frameworks that attempt to better understand and reduce injury risk (Van Mechelen et al. 1992; Finch, 2006; Meeuwisse et al. 2007; Roe et al. 2017). Although previous literature has been unable to agree upon an optimal framework in relation to injury risk reduction, these models are proposed to aid the reduction of injury risk in sport. Whilst these injury prevention frameworks have developed over recent years, these models consistently stress the importance of determining injury incidence and their associated risk factors, and using this information to inform preventative measures. However, as injury incidence remains a contemporary issue in elite cohorts of soccer players (Waldén et al. 2015; Ekstrand et al. 2016), there consequently appears a need to better practices that attempt to identify and reduce injury risk.

Although the aforementioned injury frameworks stress the importance of determining risk factors of injury, less attention has been afforded to injury risk screening. The inclusion of injury risk screening has now been included in a recent injury prevention framework in order to better understand the physical characteristics of an athlete (Roe et al. 2017). In turn, the inclusion of injury risk screening enables practitioners to identify if an athlete(s) demonstrates symptoms of suggested injury risk factors reported by previous literature. Conversely, failure to adopt screening tests would leave potential discrepancies undetected which may have implications for injury risk, and should therefore be considered in injury prevention frameworks. Although the efficacy of screening tests, such as isokinetic dynamometry, has been previously questioned in for injury risk screening risk in elite cohorts of soccer players (Bahr, 2016; Van Dyk et al. 2016; Green et al. 2018), such assessments are still advocated since strength is a modifiable risk factor for injury (Croisier et al. 2008; Van Dyk et al. 2016; Lee et al. 2017; Verhagen et al. 2018). Further literature also suggests that these observations may be a result of the procedures and metrics used to classify injury (De Ste Croix et al. 2017), and warrants further investigation.

The criticisms associated with isokinetic dynamometry may be related to the claimed lack of functional relevance (De Ste Croix et al. 2017), thus the efficacy of this screening tool may be enhanced by ensuring that these procedures are relevant to specific injuries and the associated sporting demands. As such, these considerations may enable athlete strength profiling with increased functional relevance and specificity. Therefore, including these considerations within injury risk screening as part of an injury prevention framework may more appropriately identify discrepancies and injury risk. In turn, data derived from injury risk screening can then be used to inform preventative measures and highlight training needs to reduce the risk of injury. The inclusion of injury risk screening consequently enables practitioners to better manage athletes and select the most appropriate method of correcting specific discrepancies (Roe et al. 2017). Moreover, the screening process may be repeated to identify the responses of preventative measures that can be subsequently used refine or adapt prescribed exercises. Therefore, this thesis is focused with reference to muscular strength profiling, and how screening practices associated with isokinetic dynamometry can be used with enhanced specificity to injury mechanisms and sporting demands.

To increase the functional relevance of muscular strength assessments, the interaction of contraction mode, angular velocity and joint angle must be determined and related to movements associated with injury. As it has been suggested that muscular strength is influenced by contraction mode, angular velocity and joint angle (Ayala et al. 2013; Evangelidis et al. 2015; De Ste Croix et al. 2017), these factors should be considered when quantifying muscular strength. By establishing these responses, muscular strength may subsequently be quantified at specific contraction modes, angular velocities and joint angles during movements associated with thigh musculature and knee ligament injuries with enhanced functional relevance.

However, contraction mode, angular velocity and joint angle are not typically considered concurrently when determining thigh musculature strength in elite soccer populations. As such, isokinetic dynamometry is required to sufficiently understand the interaction of contraction mode, angular velocity and joint angle in elite cohorts of soccer players in order to make inferences of thigh musculature strength during the completion of functional tasks. Based on these responses, thigh musculature strength may be quantified during the completion of functional tasks as a function of knee joint angle and angular velocity. The knee joint angles and angular velocities exhibited during the completion of functional tasks can be quantified via kinematic analysis, and may consequently be used to make inferences of thigh musculature strength. Since muscular strength is a primary modifiable risk factor for injury (Fousekis et al. 2011; Petersen et al. 2011; van der Horst et al. 2015; Augustsson and Ageberg, 2017; Attar et al. 2017), increasing the functional relevance of strength assessment may better identify potential risk factors for injury, and in turn can be used to inform preventative measures to aid the reduction of injury risk.

2.3 Epidemiology of Soccer Injuries

Injury Incidence and Severity

Epidemiological observations have identified that soccer players encounter ~3 to ~8 injuries per 1000 hours of exposure to soccer specific activity (LeGall et al. 2008; Ekstrand et al. 2009; Hägglund et al. 2009; Hartmut et al. 2010). Further observations also identify that ~83 to ~92% of total injuries are attributed to the lower extremities, where the thigh and knee regions account for ~45% (Hawkins and Fuller, 1999; LeGall et al. 2006; Tegnander et al. 2008; Ekstrand et a. 2009; Hartmut et al. 2010; Renshaw and Goodwin, 2016). Moreover, these aforementioned studies identifies of these injuries that commonly occur (~70%) without direct physical contact. Previous literature have also identified that the incidence of soccer injuries is significantly higher in elite players when compared to amateurs, and likely to be influenced by increased exposure (van Beijsterveldt et al. 2015). Overall injury incidence in elite cohorts of soccer players appears to be highest during match play, and likely to be influenced by increased demands when compared to training (Ekstrand et al. 2013; Hägglund et al. 2013; Waldén et al. 2013; Ekstrand et al. 2016). Although previous literature have primarily focused on injury incidence in senior aged male soccer players (Ekstrand et al. 2011, 2013; Hägglund et al. 2013; Waldén et al. 2013; Ekstrand et al. 2016) youths (aged 15-19 years) and females are also predisposed to increased injury risk during soccer match play, as identified in Table 2.1. The observed increased incidence in youth soccer players are attributed to the effects of adolescent growth (Hewett et al. 2004, 2015; Van Der Sluis et al. 2014, 2015), and will be further discussed in the forthcoming sections. These data suggest further attention should also be afforded to youth and female soccer players.

Table 2.1
Overall Injury Epidemiology: Gender and Age Specific (Match Hours)

Study	**Players**	**Injury Incidence**
Ekstrand et al. (2011)	Male Senior	~8/1000 hours
Le Gall et al. (2006)	Male Youth	~10/1000 hours
Hartmut et al. (2010)	Female Senior	~18/1000 hours
Le Gall et al. (2008)	Female Youth	~23/1000 hours

Further epidemiological observations have identified that KF muscular strains are the single most common injury identified across soccer playing ages and gender, accounting for ~35% of all injuries (LeGall et al 2006, 2008; Hartmut et al. 2008; Ekstrand et al. 2011). These aforementioned studies also identified that KF injuries are most commonly located on the dominant lower limb. However, when considering that youth and female soccer players possess a similar proportion of KF injuries, but possess an increased injury risk due to strength imbalances and maturational changes, it could be assumed that youth and female soccer players obtain more KF injuries when compared to senior aged males. Therefore, these cohorts of players should also be afforded increased attention in relation to injury risk reduction, despite previous literature focusing on senior aged males. These suggestions have additional importance for female soccer players who are approximately three times more likely to suffer traumatic injuries such as ACL injury when compared to their male counterparts (LeGall et al. 2008; Harmut et al. 2008; Waldén et al. 2011), with this response being further increased in youth females (Renstrom et al. 2008; Hägglund and Waldén, 2015). Further observations have also identified that the non-dominant limb suffers an increased number of ACL injuries when compared to the dominant limb, irrespective of playing age (Brophy et al. 2010; Hägglund and Waldén, 2015).

As identified in the latest Union of European Football Associations injury audit in professional male soccer players (Ekstrand et al. 2016), the incidence of KF injuries have increased annually by 4% between 2001-2014. Moreover, knee ligament injury incidence professional male soccer also elicited a similar response between 2001 and 2005 (Waldén et al. 2015). When considering youth and female soccer players have reduced sport science support relative to senior aged males, it could also be surmised that injury incidence remains a concern in these cohorts of players. The observations in professional male soccer indicate that despite the advancements in sport science and medicine, KF and ACL injuries remain a concern. This has particular importance when considering the prevalence of KF and knee ligament injuries across soccer playing ages and gender. Although injury incidence has been commonly used in previous literature to identify injury risk in elite cohorts of soccer players (LeGall et al. 2006, 2008; Harmut et al. 2008; Waldén et al. 2011; Ekstrand et al. 2011; Ekstrand et al. 2013; Hägglund et al. 2013; Waldén et al. 2013; Ekstrand et al. 2016), the severity of specific injuries also require determining to ascertain impact of injury, relative to playing age and gender. Thus, the ways in which practitioners and researchers identify and reduce injury risk may not be sufficient across different ages and genders of soccer players.

Epidemiological studies consistently use injury incidence to identify the impact of specific injuries related to soccer match-play (LeGall et al. 2006, 2008; Harmut et al. 2008; Waldén et al. 2011; Ekstrand et al. 2011; Ekstrand et al. 2013; Hägglund et al. 2013; Waldén et al. 2013; Ekstrand et al. 2016). However, it has been recently suggested that the combined effect of injury incidence and severity should both be considered for identifying injury impact (Figure 2.1) (Bahr, Clarsen and Ekstrand, 2017). These recent recommendations were advocated based on epidemiological observations between 2001-2016 in senior aged professional male soccer players (Ekstrand et al. 2013; Hägglund et al. 2013; Waldén et al. 2013; Ekstrand et al. 2016), and concluded that KF and ACL injuries are the highest priorities for injury risk reduction. For instance, although KF injuries are prevalent across playing ages and gender, average time loss for grade I, II and III tears are 17, 22 and 73 days, respectively, in professional male soccer players (Ekstrand et al. 2012). As such, it could be suggested that KF injuries do not possess a prolonged injury burden. With regards to ACL injuries, it has been identified that average time loss is ≥ 200 days in both male and female soccer players (Brophy et al. 2012; Bahr, Clarsen and Ekstrand, 2017), but possess a match play incidence of only ~5-8% for males and females, respectively (Faude et al. 2005; Hägglund, Waldén and Ekstrand, 2009; Waldén et al. 2010, 2011). It can therefore be assumed that the burden of KF injuries in youth and female soccer players would also be of concern to players and practitioners alike. Furthermore, since female soccer players are at an increased risk of ACL injury and possesses a prolonged absence (Renstrom et al. 2008; Hägglund and Waldén, 2015), the burden of these injuries would be increased in these cohorts of players, in particular to youth females. Therefore, there appears a need to prioritise the reduction of injury risk of KF and ACL injuries across soccer playing ages and genders.

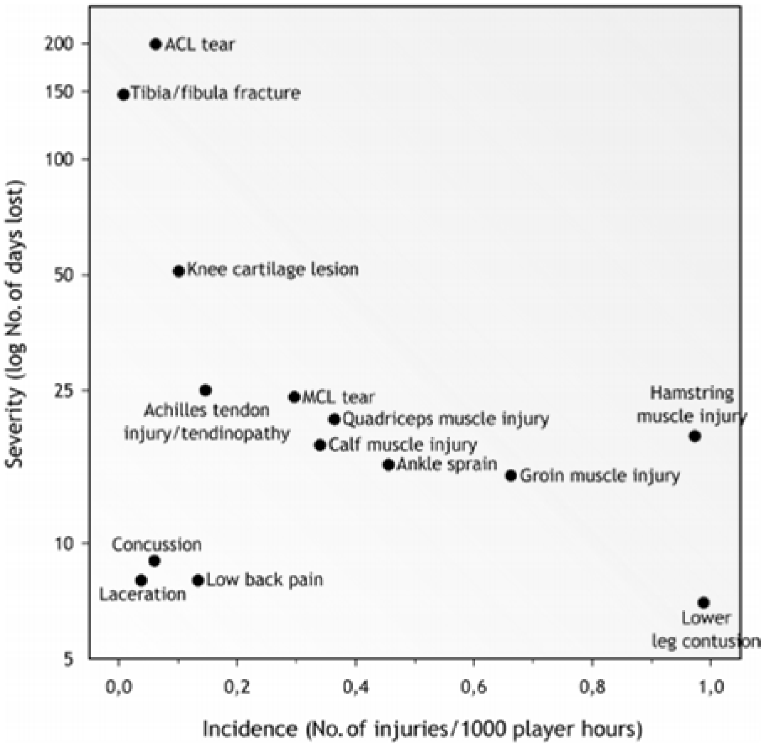

Figure 2.1 illustrates the combination of injury incidence and severity in professional senior aged soccer players. The darker colour denotes a larger injury burden (Bahr, Clarsen and Ekstrand, 2017).

Mechanisms of Knee Flexor Injuries

The occurrence of KF injuries are associated with specific movements commonly performed during soccer match-play, such as running and change of direction tasks (Hawkins and Fuller, 1999; Woods et al. 2004). For example, high-intensity running and change of direction tasks are suggested to account for ~60% of all KF injuries in professional male soccer players (Hawkins and Fuller, 1999; Woods et al. 2004), where the biarticular nature of these musculature subsequently increase muscular strain (Thelen et al. 2005; Guex and Millet, 2013). Although these data presently do not exist in youth male or female soccer players, it could be assumed that high volumes of running and change of direction activities may also influence KF injury risk in these cohorts of players. As the high-intensity distances and directional changes completed during soccer match play are comparable relative to playing age and gender (Taylor et al. 2017) suggests that these cohorts of players are exposed to similar proportions of movements associated with KF injuries.

During the completion of high-intensity running and directional changes, it is suggested that the terminal swing phase of these movements increase KF injury risk (Kivi, Maraj and Gervais, 2002; Thelen et al. 2005; Guex and Millet, 2013). Specifically, the terminal swing phase of high-intensity running and directional changes (Figure 2.2) are coincident with peak elongation stress of the musculature coupled with increased angular velocities (Kivi, Maraj and Gervais, 2002; Thelen et al. 2005; Guex and Millet, 2013), and a likely cause of injury to the myotendinous junction (Koulouris et al. 2003; Askling et al. 2007). Consequently, injury to the KF may occur when the sarcomeres are rapidly stretched beyond their optimal length, and may result in the inability of the musculature to elicit a sufficient amount of force to quickly decelerate the shank (Morgan, 1990; Morgan and Proske, 2004).The assessment of eccKF may therefore offer a more appropriate assessment of these musculatures' strength characteristics, and should be assessed at increased angular velocities.

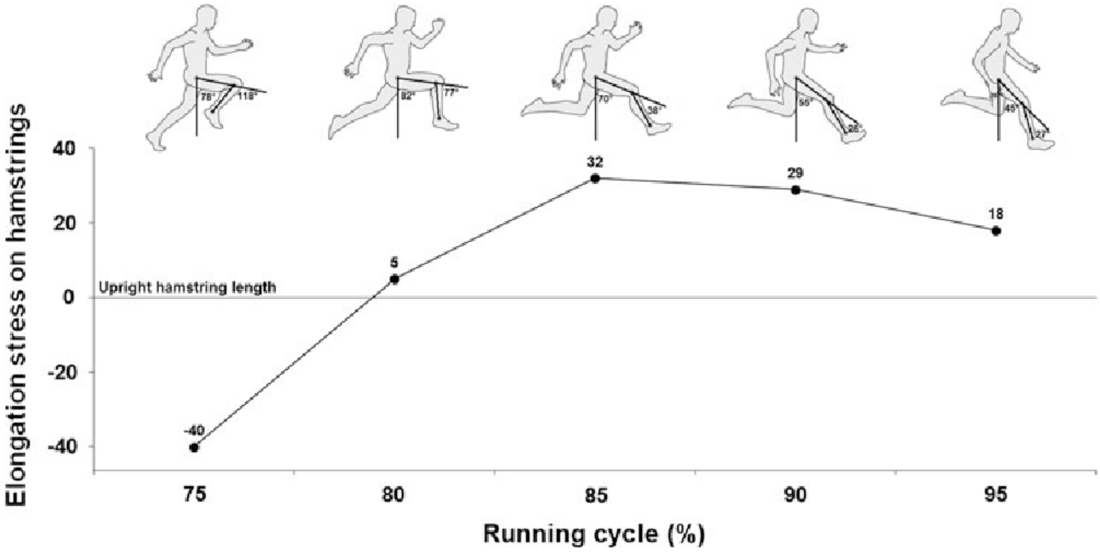

Figure 2.2 illustrates the occurrence of hamstring peak elongation stress during the late swing phase of sprinting (Guex and Millet, 2013).

Mechanisms of Anterior Cruciate Ligament Injuries

The occurrence of ACL injuries are also suggested to occur following initial ground contact (Podraza and White, 2010; Hewett and Myer, 2011; Norcross et al. 2013) during the deceleration phase of landing and change of direction tasks commonly performed during soccer match play (Brophy et al. 2014; Waldén et al. 2015). In contrast to the mechanisms associated with KF injury, both the KF and KE musculature are required to mitigate injury risk. For instance, the aforementioned movements are suggested to place the KF at increased demands to stabilise the knee joint and reduce anterior shear forces, which have been associated with ACL injury (Shimokochi et al. 2009; Hewett et al. 2010; Leppänen et al. 2017). As the KF musculature have been identified to be agonists to the ACL (Li et al. 1999; MacWilliams et al. 1999; Chmielewski et al. 2002), sufficiently developed eccentric strength of these musculature are required to reduce increased risk of injury.

At and following the period of initial ground contact during the completion of movements associated with ACL injury, it has been suggested that the KF may be contracting concentrically due to increases in knee flexion. However, it is highly questionable that increases in knee flexion would be attributed to concentric KF contractions as this would likely result in substantial loss of postural control, and failure to dissipate impact forces up the kinetic chain (Brunner and Rutz, 2013). Alternatively, Brunner and Rutz (2013) suggest the increased knee flexion following initial ground contact is due to the external flexor moments that are placed upon the knee joint, and not an action created by concentric KF contractions. Since the KF have proximal attachments to the hip joint, and are also prominent hip extensors during closed kinetic chain exercises (Yanagisawa et al. 2015; Bourne et al. 2017), these musculature would consequently contract eccentrically as the hip flexes following ground contact of functional tasks (Figure 2.3). These suggestions are in support of musculoskeletal models (Thelen et al. 2005; Schache et al. 2012) that identified eccentric KF contractions during stance, whereas no concentric contractions were identified. Therefore, it can be assumed that the eccKF are required to help dissipate ground impact forces up the kinetic chain and help stabilise the knee joint during and following initial ground contact.

Figure 2.3 the role of the hamstring musculature during and after the period of initial ground contact (Brunner and Rutz, 2013).

Due to the external knee flexor moments that are placed upon the knee joint following initial ground contact of functional tasks, an internal extensor moment is therefore required to counteract these forces. As such, the KE are required to counteract the external moments that are placed upon the knee joint. This in support of previous literature that have also identified that the KE musculature are the primary dissipaters of large impact forces during the completion of functional tasks (Podraza and White, 2010; Norcross et al. 2013), thus sufficiently developed strength of the KE may also be required to reduce ACL strain and potential injury risk. As such, it is pertinent to consider the aforementioned mechanisms associated with these injuries to help inform screening methods aimed to identify potential injury risk and inform exercise prescription.

2.4 Risk Factors for Injury

The specific causes of injury require sufficient understanding in order to inform preventative measures for the reduction of injury risk (Van Mechelen, Hlobil and Kemper, 1992; Finch, 2006; Mclean et al. 2008). In an attempt to better understand the potential causes of injury, previous literature has identified risk factors to be either modifiable or non-modifiable (Bahr and Hume, 2003; Myer et al. 2014; Price et al. 2017). The non-modifiable risk factors associated with KF and ACL injuries include previous injury, age, and gender (Hughes and Watkins, 2006; Myer et al. 2014; Price et al. 2017). The aforementioned studies also identify that thigh musculature strength and imbalances, knee abduction, and extension are modifiable risk factors for KF and ACL injuries (Sugimoto et al. 2013, 2016; Al-Attar et al 2017. As injury incidence is influenced by previous injury, playing age and gender of the soccer player(LeGall et al. 2006, 2008; Hartmut et al. 2010; Ekstrand et al. 2011), these factors will be considered within the thesis and in relation to thigh musculature strength and knee biomechanics.

Previous and Re-Injury

Literature has consistently identified that previous injury is a significant risk factor in professional soccer players (Kucera et al. 2005; Faude et al. 2006; Hägglund et al. 2006; Fulton et al. 2014; McCall et al. 2015). Although numerous factors are associated with recurrent injuries, previous observations have indicated that thigh musculature strength discrepancies may influence future injury risk, such as significantly larger bilateral strength differences between the KF and KE (Croisier et al. 2002; Hägglund et al. 2012; Freckelton and Pizzari, 2013; Lepley, 2015; Grindem et al. 2016). As such, previous research have consequently postulated that insufficient rehabilitation and return to play guides influence future injury risk (Schmitt et al. 2015; Grindem et al. 2016; Kyritsis et al. 2016). For instance, ACL reconstructed participants at the point of return to play have been shown to exhibit significant KE strength deficits in the injured limb when compared to the non-injured side (Schmitt et al. 2015; Grindem et al. 2016; Kyritsis et al. 2016), and to healthy controls. In further support of these observations, a 15 year prospective study identified that only 65% of male soccer players return to professional playing levels following ACL injury (Waldén et al. 2016). Although it is not possible to modify the injury history of a soccer player, sufficient rehabilitation and screening methods are warranted to better determine the strength characteristics of the thigh musculature to reduce future injury risk.

Following ACL reconstruction, isokinetic strength assessments of KF and KE have been used to identify rehabilitation responses and bilateral asymmetries at the point of return to play (Thomas et al., 2013; Czaplicki et al., 2015). Such literature commonly compares strength characteristics of the thigh musculature between injured and uninvolved limbs during the completion of rehabilitation. Consequently, a common return to play criteria following ACL injury identifies that bilateral strength differences of less than 10% are required for the thigh musculature, and also associated with a significant reduction of future injury risk (Lepley, 2015; Grindem et al. 2016). Whilst these observations may help to identify rehabilitation responses, it has also been suggested that the non-involved lower limb may also incur detraining effects following injury, and possess strength deficits (Hsiao et al. 2014). Comparisons to healthy controls may therefore supplement current methods that commonly use bilateral strength comparisons for determining strength discrepancies and return to play decisions.

Considering the burden of reoccurring injuries, the reduction of primary injuries are therefore required (Bahr, Clarsen and Ekstrand, 2017). For instance, as recurrent ACL injuries are common, screening and prevention of primary injury is required to reduce the high number of reinjures (Renstrom et al 2008; Hägglund and Waldén, 2016). In turn, the reduction of primary injuries would consequently have beneficial implications for decreasing the number of recurrent injuries, and lower their burden upon soccer players (Bahr, Clarsen and Ekstrand 2017). Consequently, there is also a need to screen for non-injured soccer players, with implications for reduction of potential injury risk. These considerations may also be appropriate for youth players to reduce future injury risk in these cohorts of players.

Playing Age

Playing age is a non-modifiable injury risk factor for soccer players, with these observations attributed to the effects of adolescent growth (Van Der Sluis et al. 2014, 2015). The influence of adolescent growth on injury risk has however only been considered in male players (Van Der Sluis et al. 2014, 2015). Nevertheless, the influence of adolescent growth on increased injury risk in youth soccer players has been attributed to rapid increases of skeletal length of the lower extremities, creating longer levers that require larger torques to maintain postural control without concurrent increases in muscular strength (Kaneshia et al. 1995; De Ste Croix et al. 1999; Hewett et al. 2004, 2006). This period of growth also coincides with large increases in body mass (De Ste Croix et al. 2002) which in turn, place greater demands of the thigh musculature to provide postural control and dissipate impact forces during functional movements (Hewett et al. 2004, 2015). As injury risk remains elevated following the period of adolescent growth (Van Der Sluis et al. 2014, 2015), it could be suggested that the improvements in muscular strength are disproportionate to the increases in body mass and skeletal length. As such, these factors may influence higher injury incidence in youth soccer players (10 injuries per 1000 hours of match play) (LeGall et al. 2008) when compared to senior aged players (8 injuries per 1000 hours of match play) (Ekstrand et al 2011).

It also appears that the effects of adolescent growth are also specific to gender, with females typically beginning their development at ~11 years of age when compared to ~14 in males (Abbassi, 1998; Granados, Gebremariam and Lee, 2015). The increases in musculature strength is also relative to gender, with these developments plateauing at ~14 years of age in females when compared to ~17 years of age in males (De Ste Croix et al. 1999). Since injury risk remains elevated following the period of adolescent growth in youth soccer players, the magnitude of musculature strength developments may not be sufficient to reduce the increased injury risk in these cohorts of players, and may be specific to gender. In further support, additional research identified that youth female's countermovement jump heights do not significantly improve during the period of adolescent growth (Hewett et al. 2006), suggesting that lower limb musculature strength may not sufficiently develop relative to the increases in body mass and skeletal length. As these trends were not demonstrated by males (Hewett et al. 2006), it has been postulated that during and following the completion of adolescent growth, female soccer players may be predisposed to an increase injury risk due to a higher relative weakness of the thigh musculature. These observations may therefore contribute to the discrepancies between different soccer playing ages and genders in relation to injury incidence, but are limited since countermovement jumps cannot identify discrepancies of specific musculature. There is limited literature that identifies strength deficits and imbalances of specific thigh musculature groups following adolescent growth (Forbes et al. 2009; Iga et al 2006, 2009). As a result, it is currently unclear if youth male and female soccer players possess increased thigh musculature strength discrepancies when compared to their senior counterparts, and warrants future research.

The effects of adolescent growth have also been attributed to the increased ACL injury risk in youth female soccer players (Renstrom et al. 2008, Hägglund and Waldén, 2016). In addition to the limited developments in muscular strength, youth females have also demonstrated alterations in lower limb biomechanics during functional tasks, where knee abduction angles and moments were observed to significantly increase throughout the period of adolescent growth that may increase ACL injury risk (Hewett et al. 2004, 2015). As these trends were not noted in youth males (Hewett et al. 2004, 2015), it can be suggested that youth female soccer players may also be at further risk of ACL injury during and following the onset of adolescent growth that persists into adulthood. Previous literature have also yet to identify whether senior and youth female soccer players exhibit different movement patterns, and would be particularly important to ascertain if youth players are sufficiently conditioned to manage the increased demands of soccer in an attempt to reduce potential injury risk (Söderman et al. 2001; Van Der Sluis et al. 2014; Wrigley et al. 2012; Taylor et al. 2017).

Gender

Although a non-modifiable risk factor, gender also appears to influence injury risk in soccer players (LeGall et al. 2006, 2008; Renstrom et al. 2008; Waldén 2011). The purported increased injury risk in female soccer players has been associated with enlarged KE moments that are exhibited during the completion of functional tasks when compared to males (Shimokochi et al. 2009; Hewett et al. 2010; Leppänen et al. 2017). Moreover, females are also identified to exhibit significantly higher knee abduction angles and moments during functional movements when compared to males due to increased ligament strain (Ford, Myer and Hewett, 2003; Russell et al. 2006; Kiapour et al. 2014). Consequently, these observations have led to suggestions that increased knee abduction and extensor moments are associated with increased injury risk, in particular to the ACL (Olsen et al. 2004; Hewett et al. 2004, 2005, 2010, 2015; Waldén et al. 2015). However, biomechanical assessments of functional tasks in elite female soccer players are currently limited in literature, and seem somewhat surprising when considering the severity and prevalence of ACL injuries in these cohorts of players. As such, it is unknown whether female soccer players exhibit knee abduction angles and moments during the completion of functional tasks that may influence increased injury risk. It is also currently unknown whether youth female soccer players possess increased knee abduction and extensor moments that could be indicative of an impaired ability to maintain postural control and increased injury risk. Biomechanical assessments of functional tasks are therefore required to identify if these cohorts of players exhibit large knee abduction and extensor moments that are indicative of increased injury risk.

It has also been suggested that females possess significantly higher strength imbalances between the KF and KE musculature when compared to males (Rosene, Fogarty and Mahaffey, 2001; Hewett et al. 2008, Myer et al. 2009; Andrade et al. 2012). As increased strength imbalances of the thigh musculature are suggested to be associated with increased number of KF and ACL injuries (Hewett et al. 2007; Croisier et al. 2008; Myer et al. 2009; Lee et al. 2017), these impairments could also predispose females to an increased injury risk. Although there is a plethora of research that have assessed thigh musculature strength imbalances in professional male soccer players (Gür et al. 1999; Dauty et al. 2003; Zakas, 2006; Croisier et al. 2008; Greig, 2008; Fousekis, Tsepsis and Vagenas, 2010; Fousekis et al. 2011; Van Dyk et al. 2016, 2017; Lee et al. 2017; Bakken et al. 2018), the available literature in professional female soccer players are currently limited (Jenkins et al. 2012; Manson et al. 2014). As previous studies have primarily determined thigh musculature strength imbalances in heterogeneous female populations (Rosene, Fogarty and Mahaffey, 2001; Hewett et al. 2008, Myer et al. 2009; Andrade et al. 2012), it is unknown whether senior or youth female soccer players possess muscular imbalances that may predispose these cohorts to an increased injury risk.

Thigh Musculature Strength

As identified by previous prospective studies (Croisier et al. 2008; Augustsson and Ageberg, 2017; Lee et al. 2017), soccer players who possess a reduced strength capacity of the KF are significantly more likely to suffer injury. This is supported by further findings that have identified KF injury risk is modified in soccer players who are prescribed eccentric strength training (Askling et al. 2003; Fousekis et al. 2011; Petersen et al. 2011; van der Horst et al. 2015; Attar et al. 2017). As previously alluded to, sufficiently developed eccKF strength is required to decelerate the shank (Chmielewski et al. 2002) during the terminal phase of running and change of direction activities (Woods et al. 2004; Chumanov et al. 2011; Guex and Millet, 2013). These activities are also characterised by high angular velocities, eccentric contractions, and are coincidental with peak elongation stress of the musculature (Kivi, Maraj and Gervais, 2002; Thelen et al. 2005; Guex and Millet, 2013). Although the aforementioned literature are concerned with male players, these observations were also consistent in youth female athletes (Augustsson and Ageberg, 2017). However, as Augustsson and Ageberg (2017) determined muscular strength during one repetition maximum barbell squats, this study was unable to determine strength deficits or imbalances of particular musculature, thus reducing the ability to appropriately prescribe specific exercises for injury risk reduction. Methods associated with one repetition maximum barbell squats are unable to identify strength imbalances between specific thigh musculature, which is associated with injury risk Croisier et al. 2008; Lee et al. 2017). Moreover, bilateral strength differences greater than 10% has also been associated with thigh musculature and knee ligament injuries, and also requires determining (Lepley et al. 2015; Grimdem et al. 2016). As isokinetic dynamometry is able to determine strength deficits of particular musculature (Croisier et al. 2008; Fousekis, Tsepsis and Vagenas, 2010; Lee et al. 2017), improved measures of screening muscular strength in soccer players is therefore warranted, specific to both playing age and gender.

Although absolute muscular strength has been shown to be a modifiable risk factor for KF injuries (Askling et al. 2003; Fousekis et al. 2011; Petersen et al. 2011; van der Horst et al. 2015; Attar et al. 2017), literature has also suggested that strength imbalances are associated with injury. Isokinetic dynamometry is commonly used to determine muscular strength imbalances of KF and KE in elite cohorts of soccer players (Iga et al. 2006; Daneshjoo et al. 2012; Jenkins et al. 2012; Manson et al. 2014; Lee et al. 2017). Literature has identified that higher absolute KE strength relative to the KF increases KF injury risk in professional male soccer players (Croisier et al. 2008; Lee et al. 2017). The calculation of muscular imbalances are commonly completed based on ratios determined by KF divided by KE strength values (Aagaard et al. 1995, 1998), with lower ratios than 1 indicating increased KE strength dominance (Croisier et al. 2008; Hewett et al. 2010; Lee et al. 2017). Furthermore, lower strength ratios of the KF and KE have also been previously associated with increased ACL injury risk (Hewett et al. 2008, 2010; Kim and Hong, 2010; De Ste Croix et al. 2017). Sufficiently developed KF strength are required to reduce ACL injury risk as these musculature counteract large KE forces (Chumanov et al. 2012; Higashihara et al. 2015). Therefore, this has consistently led to literature suggesting that a KE strength dominance relative to the KF is a risk factor for ACL injury (Myer et al. 2004; Hewett et al. 2010; Leppänen et al. 2017). As a result, a lower strength ratio would suggest the KF possess a reduced capacity to sufficiently decelerate the shank during the terminal swing phase of functional movements, and may increase thigh musculature and knee ligament injury risk (Chmielewski et al. 2002; Hughes and Watkins, 2006).

It has also been suggested that injury risk may be limb specific, with KF strains being identified as most prevalent in the dominant limb (preferred kicking limb) of senior male and female soccer players (LeGall et al. 2008; Ekstrand et al. 2011). Where previous studies have attempted to screen for bilateral discrepancies, they have typically quantified percentage differences between the dominant and non-dominant limbs (Schmitt et al. 2015; Grimdem et al. 2016). Such studies have identified bilateral eccKF strength deficits of 15% are associated with KF injuries in the weaker limb of professional male soccer players (Croisier et al. 2008), whereas conKE strength deficits greater than 10% predispose the weaker limb to an increased risk of future ACL injury (Lepley, 2015; Grindem et al. 2016). However, percentage differences used to determine bilateral discrepancies should also be considered with their corresponding strength values as equally impaired KF and KE strength can achieve bilateral symmetry. Consequently, to appropriately identify bilateral strength discrepancies, the associated strength values of these musculature should also be considered with normative values. Bilateral isokinetic strength assessments have been primarily conducted in senior and youth male soccer players (Croisier et al. 2008; Iga et al. 2009; Daneshjoo et al. 2013; Van Dyk et al. 2016), these procedures lack functional relevance which may account for equivocal associations with injury risk (De Ste Croix et al. 2017; Van Dyk et al. 2016; 2017). Moreover, isokinetic strength assessments have yet to be determined in senior and youth female soccer players. Bilateral strength assessments using isokinetic dynamometry would be able to determine strength characteristics and discrepancies specific to the lower limb, and in turn may be important for reducing potential injury risk. As such, it remains unclear whether senior and youth female soccer players possess bilateral strength differences of the thigh musculature that may have potential implications for KF and ACL injuries.

Knee Biomechanics

As female soccer players are also predisposed to ACL injuries, specific movements have been identified to increase the risk of these injuries, and suggested as modifiable (Sugimotio et al. 2012, 2016). For instance, cadaveric studies have identified that ACL strain significantly increases with higher knee abduction coupled with knee extension (Seering et al. 1980; Stapleton et al. 1998; Kiapour et al. 2014). These observations consequently suggests multi-planar movements may predispose athletes to an increased risk of ACL injury (Quatman et al. 2010), and as such, these movement patterns require determining via motion capture during the completion of functional tasks. Whilst 2D motion capture is an accessible and cost effective option for determining biomechanical parameters exhibited during the completion of functional tasks, this tool is unable to quantify transverse plane motions. This may be particularly problematic during change of direction tasks where tibial rotation of the knee joint may be incorrectly classified during frontal plane motions, thus influencing knee valgus values. These observations are further supported by previous literature that have demonstrated moderate correlations for kinematic data recorded in the frontal plane between 2D and 3D assessments of functional tasks, with these relationships diminishing during single limb activities (Maykut et al. 2015; Herrington et al. 2017; Schurr et al. 2017). Furthermore, 2D motion capture cannot calculate the joint moments that are placed upon the knee joint. These considerations are particularly important for this present thesis since increased knee abduction and extensor moments have been associated with increased injury (Hewett et al. 2005; Leppänen et al. 2017). As such, 3D motion capture is identified as the criterion measure for quantifying biomechanical parameters.

In addition to the aforementioned literature that identified differences in 2D and 3D motion capture, it has also been revealed that different planes of motion exhibit varying levels of reliability. For instance, the sagittal plane has been shown to elicit high levels of reliability during the completion of functional tasks (intraclass correlation coefficients [ICC ≥ 0.95]) (Ford et al. 2007). Frontal plane motion has also yielded acceptable reliability during the completion of functional tasks (ICC ≥ 0.70) (Ford et al. 2007), whereas transverse plane movements have been shown to elicit questionable reliability (ICC ≥ 0.59). Whilst transverse motions such as internal/external rotation appear to influence risk of ACL injuries (Quatman et al. 2010; Kiapour et al. 2014), these measures should be interpreted with caution. Therefore, it appears that sagittal and frontal planes of motion are most appropriate to determine movement patterns associated with injury risk.

Whilst sagittal and frontal planes of motion appear to produce reliable data, these planes of motion have also been previously associated with increased injury risk during the completion of functional tasks. For instance, increased knee abduction angles and moments exhibited during drop landing tasks have been suggested to be associated with increased ACL injury (Hewett et al. 2005; Shimokochi et al. 2009; Waldén et al. 2015; Leppänen et al. 2017). However, a recent prospective study of elite female handball and soccer players identified no statistically significant association between knee abduction angles and moments during vertical drop landing tasks in injured participants (Krosshaug et al. 2016). These equivocal findings may be attributed to the different participants used in the aforementioned studies. Moreover, the ambiguous observations have also been associated with the use of drop landing tasks, and have limited association with movements related to ACL injuries (Kristianslund and Krosshaug, 2013; Kristianslund et al. 2014). Since single leg change of direction activities place increased demands of the lower limb to maintain postural control when compared to drop landing tasks (Olsen et al. 2004; Pappas et al. 2007), these movements have consequently been associated with increased risk of ACL injury. As ACL injury risk has also been identified to be increased during movements that place large multiplanar demands upon the knee joint (Jindrich et al. 2006; Quatman et al. 2010; Kristianslund and Krosshaug, 2013; Kristianslund et al. 2014), the use of single limb change of direction tasks may be more sensitive to identify discrepancies associated with injury. Consequently, these movements have been suggested to better determine factors associated with injury with enhanced specificity to the mechanisms associated with ACL injury.

Previous literature have also suggested that increased KE moments are associated with increased ACL risk (Shimokochi et al. 2009; Hewett et al. 2010; Leppänen et al. 2017). Despite these observations, previous literature have not appropriately considered the strength capacities of the thigh musculature relative to the moments placed upon the knee joint, and may have potential implications for injury risk. Although it has been previously suggested that increased KE moments place an additional requirement of the KF musculature to oppose these large anterior shear forces (Seering et al. 1980; Stapleton et al. 1998; Chumanov et al. 2012; Kiapour et al. 2014; Higashihara et al. 2015), the importance of KE strength is commonly disregarded. As further research identifies the KE musculature are the primary dissipaters of impact forces (Podraza and White, 2010; Norcross et al. 2013), sufficiently developed muscular strength are required to reduce the demands placed upon the knee ligaments during functional tasks (Hughes and Watkins, 2006; Schmitt et al. 2015; Kyritsis et al. 2016). Consequently, the previous observations that identified increased KE moments as a risk factor for ACL injury are unable to identify if the thigh musculature were sufficiently developed to manage the demands placed upon the knee joint. Identifying the strength capacities of the thigh musculature relative to the moments placed upon the knee joint may be important for identifying if these demands are disproportionate, and may be indicative of an increase injury risk. Therefore, future screening procedures may wish to consider the strength capacities of the thigh musculature relative to the moments placed upon the knee joint to better determine factors that may be associated with injury risk. As strength is a primary modifiable risk factor for injury, methods that characterise musculature strength with enhanced relevance to movements associated with injury may enhance the specificity of screening practices.

2.5 Screening Thigh Musculature Strength

Injury incidence remains an issue in elite soccer players, and relative to injury status, playing age and gender (LeGall et al 2006, 2008; Hartmut et al. 2010; Ekstrand et al. 2011). It has also been identified that soccer playing age, injury status, and gender appear to influence thigh musculature strength characteristics (Greig, 2008; Iga et al. 2009; Manson et al. 2013). Therefore, there appears a need to determine the strength characteristics of these cohorts of players to identify strength discrepancies and inform preventative measures. Furthermore, when considering that senior and youth female soccer players are predisposed to an increased risk of ACL injury, biomechanical assessments of functional movements in these cohorts of players are also required. However, literature has yielded equivocal results between measures of muscular strength in relation to KF and ACL injuries (Hewett et al. 2005; Croisier et al. 2008; Pauda et al. 2014; Krosshaug et al. 2016; Van Dyk et al. 2016, 2017; Lee et al. 2017; Bakken at al. 2018). As such, the procedures and metrics used to determine thigh musculature strength and knee biomechanics may be insufficient for determining potential injury risk, thus require further consideration when developing screening methods.

Isokinetic Strength Assessments

Isokinetic dynamometry is identified as the criterion measure for muscular force (Stark et al. 2011), and frequently identified as a reliable tool for determining thigh musculature strength (Maffiuletti et al. 2007; Impellizzeri et al. 2008). Other measurement tools such as isometric mid-thigh pulls and 1 repetition maximums (1RM) of the lower extremities are also viable options for quantifying muscular strength of the lower extremities. However, these aforementioned measurement tools are unable to concurrently assess thigh musculature strength characteristics at different contraction modes, angular velocities and joint angles that influence muscle force production. Moreover, isometric mid-thigh pulls and 1RM are unable to assess strength characteristics of specific musculature, such as the KF and KE. As a consequence, these measurement tools are unable to determine strength imbalances between the KF and KE associated with increased risk of injury. Moreover, isometric mid-thigh pulls and 1RM are also unable to identify bilateral strength differences, whereas isokinetic dynamometry can determine large strength deficits between lower limbs. As such, isokinetic dynamometry has been frequently used to characterise thigh musculature strength in senior aged professional male soccer players (Dauty et al. 2003; Croisier et al. 2008; Greig, 2008; Fousekis, Tsepsis and Vagenas, 2010; Fousekis et al. 2011; Van Dyk et al. 2016, 2017; Lee et al. 2017; Bakken et al. 2018) and youth soccer players (Gür et al. 1999; Kellis et al. 1999; Iga et al. 2006; Daneshjoo et al. 2012, 2013). Limited literature exists in relation to female players of different playing ages (Jenkins et al. 2012; Manson et al. 2014).

Isokinetic Testing Velocities

In relation to the assessment of thigh musculature strength using an isokinetic dynamometer, the influence of angular velocity during these assessments must be considered, and associated with the force-velocity relationship. The force-velocity relationship has been consistently used in previous literature to identify the response of different joint angular velocities and their subsequent effect on muscle force production in both concentric and eccentric contractions (Kawamori et al. 2004, 2006). In relation to concentric actions, a variety of studies have identified that with increased joint angular velocity, force production decreases. In contrast, muscular force production has been identified to increase during lower joint angular velocities (Greig, 2008; Greig and Siegler, 2009; Small et al. 2010; Evandeligis et al. 2015; De Ste Croix et al 2017). In relation to eccentric muscular actions, previous literature reveals equivocal responses when assessed at different angular velocities. Specifically, some studies have identified eccentric force production increases with higher contraction velocities (Greig, 2008; Greig and Siegler, 2009; Small et al. 2010), whereas others have shown a consistent response across a variety of velocities (Rocha, 2011; Evandeligis et al. 2015; De Ste Croix et al 2017). As such, the force-velocity responses of muscular force production require consideration during the assessment of muscular strength.

The assessment of musculature strength at different contraction velocities can also be used to identify additional training needs and training responses. This is particularly important since training at specific contraction speeds can modify muscle strength when assessed at comparable joint angular velocities (Kawamori et al. 2004; 2006), and consequently influences the shape of the force-velocity curve. These aforementioned studies identify that increasing strength values recorded at slow angular velocities would increase the gradient of the force-velocity curve, as illustrated by Figure 2.4. Similarly, this figure also demonstrates that increased strength recorded at high angular velocities would decrease the gradient of the force velocity curve. Similar responses have also been identified in relation to eccentric actions (Melo et al. 2016), albeit with this evidence being scarce in current literature. Nevertheless, quantifying muscular strength at a variety of different angular velocities can identify specific strength discrepancies, which in turn can be used to inform athlete management and development, and reassessed following an intervention.

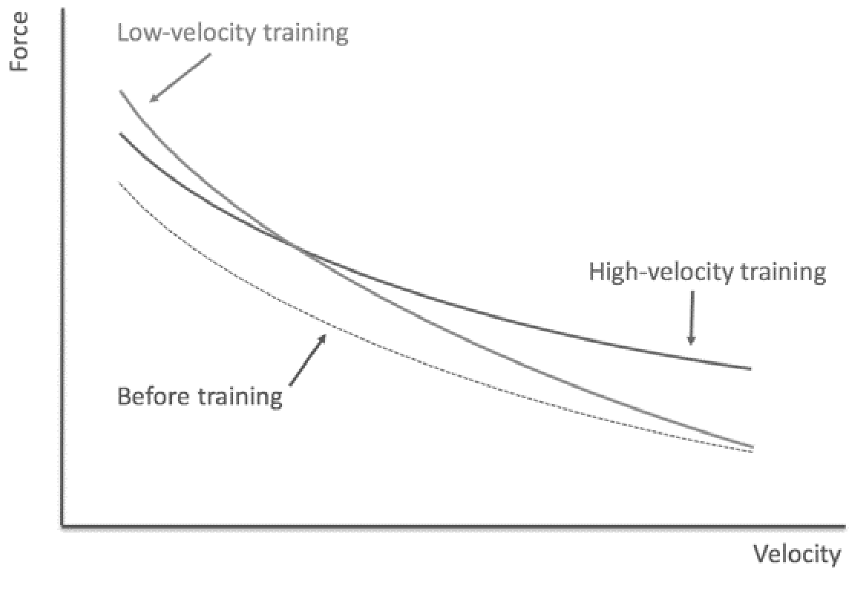

Figure 2.4 the effects on velocity specific strengthening exercises on the force-velocity relationship (Jiménez-Reyes et al. 2016).

Isokinetic strength assessments of the thigh musculature commonly utilise angular velocities of 60°·s^{-1} (Thomas et al., 2013; Czaplicki et al., 2015; Dauty et al. 2017; Van Dyk et al. 2016, 2017). Such testing velocities are used to obtain sufficient isokinetic data over a defined load range (Brown et al. 1995; Findley et al 2006). However, it has been previously suggested that isokinetic dynamometry does not resemble functional movements (Abernethy et al. 1995; Toonstra and Mattacola, 2013). In an attempt to increase the functional relevance of isokinetic strength assessments, additional testing velocities have also been used to determine muscular strength (Greig, 2008; Daneshjoo et al. 2012, 2013; Evangelidis et al. 2015; De Ste Croix et al. 2017). The inclusion of higher testing velocities during isokinetic strength assessments are supported by previous observations identifying knee angular velocities of ~400°·s^{-1} are exhibited during change of direction tasks (Nedergaard et al. 2014) which are common to soccer match-play (Bloomfield et al. 2007) and which have previously been associated with lower limb injury risk (Hawkins and Fuller, 1999; Boden and Dean, 2000; Brophy et al. 2014).

Increased isokinetic testing velocities have previously identified significantly lower concentric KF and KE peak torque (PT) in male soccer players (Greig, 2008; Daneshjoo et al. 2012, 2013), thus knee angular velocity highly influences concentric contraction force. Although not observed in elite soccer populations, further findings have identified that eccentric PT of KE and KF remain stable across a variety of isokinetic testing velocities (Evangelidis et al. 2015; De Ste Croix et al. 2017). Despite these common responses, assessments of eccKF and conKE PT across a variety of angular velocities are limited in professional cohorts of soccer players. Nevertheless, angular velocities exhibited during movements associated with injury would likely elicit higher dynamic control ratio (DCR) values (Hewett et al. 2008; Evangelidis et al 2015; De Ste Croix et al 2017. These observations would consequently be attributed to diminished conKE strength when compared to eccKF with increased knee angular velocity, when considering the previous responses of these musculature. These observations would be contrary to popular belief that conKE strength dominance relative to the eccKF is a risk factor of thigh musculature and knee ligament injuries (Hewett et al. 2007, 2010; Croisier et al. 2008; Lee et al. 2017; Leppänen et al. 2017). Therefore, isokinetic strength assessments of conKE and eccKF should be considered specific to testing velocities that better resemble movement profiles of functional tasks

Despite the influence of knee angular velocity on thigh musculature strength and their associated DCR's, these factors are not considered in recent prospective studies (Van Dyk et al. 2016, Bakken et al. 2018). These studies identified no significant differences in thigh musculature strength and DCR's in senior aged professional male soccer players who subsequently suffered KF injury when compared to non-injured players (Van Dyk et al. 2016; Bakken et al. 2018). Specifically, eccKF PT values were not significantly different between injured and non-injured players of these studies, although eccKF strength was only determined at $60°\cdot s^{-1}$. As such, it is unknown whether additional strength deficits and imbalances may have been identified between injured and non-injured soccer players at angular velocities that better represent functional movements. These studies also demonstrated that DCR values were not significantly associated with KF injury; however, muscular imbalances were calculated by data recorded at 60 and $300°\cdot s^{-1}$ for eccKF and conKE, respectively. As previously described, isokinetic testing velocities highly influence strength characteristics of KF and KE, and in turn may have influenced the DCR values used to differentiate between injured and non-injured players in these prospective studies. Thigh musculature strength assessments of eccKF and conKE are consequently required at matched velocities that better resemble functional movements to determine muscular strength deficits and imbalances of elite soccer players.

The use of additional testing velocities to determine eccKF and conKE PT may also better reflect training responses relative to the force-velocity curve. For instance, previous studies have demonstrated that velocity specific strength training elicits superior strength adaptations at the coincident testing velocity (Kawamori et al. 2004, 2006). Despite these observations, the slope of the force-velocity curve appears to have been afforded little attention in previous literature, and may identify training requirements for soccer players. For example, when considering the concentric force-velocity curve, a greater slope would be indicative of either superior strength at slow velocities or reduced strength at higher velocities. The use of additional angular velocities are also advocated by previous research in professional male soccer players that have yielded sufficient reliability for eccKF and conKE at 60, 180 and 300°·s^{-1} (Greig, 2008). However, due to dynamometer constraints, extreme angular velocities provide a minimal load range, thus limiting the choice of testing velocities (Drouin et al. 2004). As such, equipment should be appropriately used within their constraints to appropriately identify strength characteristics and player training needs at functionally relevant knee angular velocities.

Angle Specific Measures of Thigh Musculature Strength

As the magnitude of muscular force development is dependent on its length, the influence of knee joint angle will consequently influence KF and KE strength. Such responses elicited during muscular force production can be attributed to the length-tension relationship during maximal contractions. The length-tension relationship identifies where fibres display different levels of maximal force production when defined at different lengths (Gordon et al. 1966). These responses are suggested to be related to the amount of sarcomere overlap that occurs within muscle groups (Brughelli and Cronin, 2007), whereby too much or too little overlap results in sub-optimal force production. Although the length-tension relationship is concerned with single muscle fibres, this phenomenon can express length and tension via joint angle and torque, respectively, during isokinetic dynamometry (Brughelli and Cronin, 2007). Whilst length-tension responses during isokinetic dynamometry are further influenced by muscle architecture, tendon properties and joint design (Brughelli and Cronin, 2007), studies that have assessed the torque-angle relationship have clearly identified the influence of joint angle on muscular force production (Ayala et al. 2013; Cohen et al. 2015; Evangelidis et al. 2015 De Ste Croix et al. 2017).

The torque-angle relationship of muscle groups has been primarily determined via isometric contractions at a variety of joint angles (Alegre et al. 2006; 2014; Noorkõiv et al. 2015). Due to the numerous maximal contractions required during isometric strength assessments at different joint angles, these assessments may elicit a fatigue response that may influence the torque-angle curve. As such, isokinetic strength assessments have been more recently utilised to determine the torque-angle curve (Ayala et al. 2013; Cohen et al. 2015; Evangelidis et al. 2015 De Ste Croix et al. 2017). In turn, this can identify the angle of peak torque, and identify the optimal angle for muscle force production. Although the reliability of angle of peak torque has been previously questioned (Ayala et al. 2013), literature does identify that KF peak torque is ~40º, and 70º for the KE (Small et al. 2010). Thus, there appears a need to define muscular strength at specific joint angles relevant to functional tasks associated with injury.

It has also been suggested by previous literature that the torque-angle curve is modifiable through an appropriate training stimuli (Barak et al. 2004; Mcmahon et al. 2014). There are numerous studies that have demonstrated the angle of peak torque during isokinetic strength assessments occur at increased lengths in various muscle groups (Ayala et al. 2013; Cohen et al. 2015; Evangelidis et al. 2015 De Ste Croix et al. 2017). With specific reference to the thigh musculature, further observations yielded from literature demonstrate that an eccentric Nordic hamstring training programme shifts the angle of peak torque to increased lengths for the KF, and may influence strength developments (Brughelli et al. 2010). These responses have been attributed to an increased number of sarcomere which results in greater force production at increased muscle lengths (Rassier et al 1999; Leiber et al. 2000). The role of titin has also been suggested to be an important factor in eccentric muscle contractions which has been proposed to store and release elastic energy by altering spring length and stiffness (Herzog, 2014). However, the precise mechanisms associated increased muscular force production at longer muscle lengths is not entirely understood; nevertheless, these observations do identify the modifiable nature of the torque-angle curve. Since the torque-angle curve is modifiable through an appropriate training intervention, the consideration of thigh musculature strength across an angular range would identify where the muscle is strongest and weakest. As such, potential injury risk and training interventions could be determined when muscular strength is quantified across range of motion, and warrants further investigation.

In order to increase the functional relevance of isokinetic strength assessments of the thigh musculature, the metrics used to determine muscular strength and imbalances require further considerations. Practitioners and researchers commonly report isokinetic PT of the musculature that are subsequently used to determine the DCR

(Gür et al. 1999; Kellis et al. 2001; Croisier et al. 2008; Augustsson and Ageberg, 2017; Lee et al 2017). Musculature PT of the lower extremities quantifies the muscle's absolute strength capacity, and is able to identify significant differences in soccer playing ages (Gür et al. 1999; Kellis et al. 2001) and strength deficits/imbalances in players who subsequently suffer injury (Croisier et al. 2008; Augustsson and Ageberg, 2017; Lee et al 2017). However, the use of angle-specific measures have recently been advocated to supplement isokinetic strength assessments by identifying the KF's and KE's strength capacities at matched angles where injury risk reportedly increases (El-Ashker et al. 2015; De Ste Croix et al. 2017). Consequently, the sole use of PT and DCR to determine injury risk may be inappropriate. In further support, previous observations have identified that conKE PT occurs at ~70° of knee flexion, and ~40°of knee flexion for eccKF PT, thus DCR quantifies strength imbalances from data obtained at different knee joint angles (Forbes et al. 2009; Small et al. 2010; El-Ashker et al. 2015; De Ste Croix et al. 2017). The determination of angle-specific measures may better identify strength deficits and imbalances where injury is more likely to occur (Boden and Dean, 2000; Chumanov et al. 2012; Higashihara et al. 2015).

Recent studies have determined angle-specific torques and DCR's in recreational, amateur and semi-professional male soccer players (Cohen et al. 2015; Evangelidis et al. 2015). When considering that lower DCR values have been previously suggested by literature to increase KF and ACL injury risk, the aforementioned studies identified DCR's at 30º of knee flexion, indicative of eccKF strength dominance. Therefore the aforementioned findings did not identify a conKE strength dominance at joint angles where KF and ACL injuries are likely to occur (Hewett et al. 2007, 2010; Croisier et al. 2008; Lee et al. 2017) and further advocates the importance of the eccKF to provide dynamic stability for the knee joint (Hughes and

Watkins, 2006). Moreover, it was also identified that amateur and semi-professional soccer players exhibited DCR values of ~1.5 at 30º knee flexion (Cohen et al. 2015; Evangelidis et al. 2015) and were notably higher when compared to 0.8 in healthy males (El-Ashker et al. 2015), thereby suggesting these metrics may be influenced by prolonged exposure to soccer-specific activity and conditioning. In turn, these additional isokinetic strength metrics may also be able to differentiate between senior and youth soccer players with pronounced differences in exposure to soccer specific activity and conditioning. This is supported by previous findings that identified significant differences in KF and KE strength between senior and youth male soccer players (Gür et al. 1999; Kellis et al. 2001), thus able to inform exercise prescription relative to playing age. These metrics could be advantageous in identifying whether youth soccer players who begin to play against senior aged players are conditioned to cope with these increased demands (Wrigley et al. 2012; Taylor et al. 2017).

Angle-specific measures of muscular strength and imbalances have received further attention in recent years to better the functional relevance of these assessments, but such studies are currently limited in elite soccer players. However, a recent prospective study identified angle-specific DCR's at 50, 40 and 30º of knee flexion were not significantly different between injured and non-injured senior aged professional male soccer players (Van Dyk et al. 2017). Although this study does not recommend the use of angle-specific DCR's for identifying KF injury risk, Van Dyk et al. (2017) did not consider their associated torque values, despite previous observations identifying strength deficits are associated with lower limb injury (Croisier et al. 2008; Augustsson and Ageberg, 2017; Lee et al. 2017). As a result, this study was not able to determine strength deficits in soccer players who subsequently suffered injury. Therefore, the DCR must also be considered with their corresponding strength values to better identify discrepancies of the eccKF and conKE. For instance, equally impaired strength of the eccKF and conKE can still exhibit strength ratios of 1, thereby displaying perfect muscular balance. The absence of angle-specific torques of the eccKF and conKE in this study must be considered as a limitation, and should be reported in future studies.

Torque-Angle Curves

Additional metrics associated with the torque angle curve have been proposed in previous literature (Dvir, 2014). It has been suggested the torque angle-curve may be analysed through calculating work during isokinetic muscular contractions. Work performed across range of motion can be determined when multiplying force by angular displacement (measured in Joules), which is equal to the energy expended to exert 1Nm of force. Greater work performed in the torque angle-curve is attributed to an increased capacity to produce muscular force over an angular range (Dvir, 2014). Work is also suggested to identify knee injury risk in female athletes across a variety of sports, where these observations revealed work performed for concentric KF and KE actions at $300°\cdot s^{-1}$ were significantly lower in players who subsequently suffered injury when compared to non-injured participants (Devan et al. 2004). Moreover, work performed has also been identified as a reliable measure in healthy males and females (Maffultettit et al. 2007). Such findings appear to support the use of work performed across the torque-angle curve to determine muscular strength across an angular range, although this has been contested by previous literature. In a critical review of the literature, Dvir (2014) discussed the use of appropriate parameters of isokinetic strength, and concluded that work could be a redundant measure. Given the high correlations reported between work and PT, and the amount of work performed across an angular range depends on force magnitude, it appears that work performed is more indicative of absolute strength rather than the ability to produce force across an angular range. Since knee range of motion and angular velocities are standardised during isokinetic strength assessments, PT can only manipulate work performed in the torque angle-curve. As the torque angle-curve is not well considered in soccer players, further research is required to better determine isokinetic parameters that assess the musculature's ability to sustain force across an angular range. This may be particularly important in order to profile thigh musculature strength at knee joint angles that better reflect movements associated with lower limb injuries. Although isokinetic dynamometry can determine strength imbalances between KF and KE that have been previously associated with ACL injuries, biomechanical assessments of functional tasks are also used to determine injury risk.

Although recent prospective studies have questioned the ability of isokinetic strength assessments to identify injury risk in senior aged professional male soccer players, the procedures and metrics utilised in previous literature may be insufficient to profile muscular strength and identify injury risk. As muscular strength deficits and imbalances place both the thigh musculature and knee ligaments at increased risk of injury, isokinetic strength assessment should better consider the aetiology of these injuries. The procedures and analytical approaches associated with isokinetic strength assessments of KF and KE typically quantify strength deficits and imbalances at slow testing velocities, focusing on PT and DCR. Although these procedures have previously identified significant differences between injured and non-injured soccer players, angle-specific measures determined across angular velocities may further identify factors associated with injury and identify further training needs. Such considerations have not been appreciated in previous studies, and have yet to be appropriately identified in elite soccer populations of different ages and gender. Although isokinetic dynamometry can determine strength imbalances between KF and KE that have been previously associated with ACL injuries, biomechanical assessments of functional tasks are also used to determine injury risk.

Motion Analysis

As female soccer players are predisposed to an increased number of ACL injuries, biomechanical assessments of functional tasks should be used to determine the parameters associated with injury. As ACL injuries are further exacerbated in youth female soccer players (Renstrom et al. 2008; Hägglund and Waldén, 2015), biomechanical assessments of functional tasks should also be considered in this population. The increased number of injuries identified in youth female soccer layers have been attributed to effects of adolescent growth that coincide with the development of enlarged strength discrepancies (Hewett et al. 2015; Augustsson and Ageberg, 2017), thereby reducing the ability to maintain postural support and may influence injury risk.

Vertical Drop Landings

Literature consistently identifies that increased knee abduction coupled with knee extension is associated with increased ACL injury risk in females (Hewett et al. 2005; Shimokochi et al. 2009; Waldén et al. 2015; Leppänen et al. 2017). Biomechanical assessments commonly adopt bilateral vertical drop landing assessments in an attempt to identify the aforementioned discrepancies (Hewett et al. 2005; Kernozek et al. 2005; Kristianslund and Krosshaug, 2013; Fox et al. 2017). The common use of bilateral vertical drop landing tasks that are used to assess lower limb injury risk appears to be influenced by the findings of a prospective study by Hewett et al. (2005). This study identified significantly higher knee abduction angles and moments in subsequently injured participants during the completion of a drop landing task. Despite literature (Shimokochi et al. 2009; Waldén et al. 2015; Leppänen et al. 2017) commonly citing the drop landing procedure as described by Hewett et al. (2005), it must be noted that Hewett and colleagues only identified differences in 9 participants who subsequently suffered an ACL injury, thus questioning the statistical power of this study. Further prospective studies (Pauda et al. 2014; Krosshaug et al. 2016) used biomechanical assessments of vertical drop landings to determine knee injury risk in male/female cadets and female soccer/handball players. The aforementioned studies identified 117 (Pauda et al. 2014) and 42 knee ligament injuries (Krosshaug et al. 2016), and revealed no significant differences in knee biomechanics between subsequently injured and non-injured participants during bilateral vertical drop landings. Despite the larger cohorts and number of knee ligament injuries reported, knee abduction angles and moments were not associated with injury risk. The aforementioned literature raises questions about the specificity and sensitivity of bilateral drop landings in identifying discrepancies in lower limb biomechanics that are associated with injury risk.

Cutting Manoeuvres

Further criticisms of the functional relevance of drop landing tasks has been made within the literature (Kristianslund and Krosshaug, 2013; Kristianslund et al. 2014), with suggestions that single limb change of direction tasks may offer a better alternative given their association with lower limb injury risk (Boden and Dean, 2000; Olsen et al. 2004; Pappas et al. 2007; Sigward and Powers, 2006; Landry et al. 2007; Ford et al. 2011 Ortiz et al. 2011; Vanrenterghem et al. 2012; Imwalle et al. 2013; Kristianslund and Krosshaug, 2013; Fox et al. 2017). The sidestep cutting manoeuvre is a multiplanar movement which is associated with increased medio-lateral impact forces, and places higher multiplanar demands when compared to tasks such as vertical drop landings (Jindrich et al. 2006). It has consequently been suggested that sidestep cutting manoeuvres may better determine injury risk (Sharir et al. 2016). Literature is however limited with respect to utilising these side stepping manoeuvres to assess biomechanical discrepancies between playing ages of female soccer players.

Previous literature typically conducts cutting manoeuvre tasks using a sidestep technique (Boden and Dean, 2000; Olsen et al. 2004; Pappas et al. 2007; Sigward and Powers, 2006; Landry et al. 2007; Ford et al. 2011 Ortiz et al. 2011; Vanrenterghem et al. 2012; Imwalle et al. 2013; Kristianslund and Krosshaug, 2013; Fox et al. 2017), with little focus on crossover cutting manoeuvres. Where previous studies that have compared between cutting manoeuvres, they have typically reported equivocal findings with some studies identifying higher knee abduction angles and moments during sidestep tasks (Besier et al. 2001; Potter et al. 2014), whereas others identified higher values during the completion of crossover manoeuvres (Malinzak et al. 2001; Harrison et al. 2008; Ortiz et al. 2011). The aforementioned studies may have yielded equivocal results due to the different methods and participants used. Nevertheless, previous attempts to determine the biomechanical markers associated with knee ligament injuries may therefore not thoroughly profile injury risk due to the common disregard of crossover cutting manoeuvres. Biomechanical assessments of cutting manoeuvres should therefore consider both sidestep and crossover manoeuvres in relation to potential injury risk.

Consideration also needs to be made in relation to the angle of cut. A large range of cutting angles (30-180º) have previously been used during the completion of these cutting tasks (Besier et al. 2001; Landry et al. 2007; Greg, 2008; Haven and Sigward, 2014; Vanrenterghem et al. 2012; Sankey et al. 2015). Where studies have utilised a larger cutting angle, they have typically recorded higher knee abduction angles and moments during cutting manoeuvres, thus aiding the use of these methods to determine potential injury risk (Imwalle et al. 2009; Havens and Sigward, 2015; Sigward et al. 2015). However, the functional relevance of these extreme cutting angles (i.e. 90-180º) is questionable. In support, ~83% of change of direction tasks during soccer match play occur within a 0-45º range (Bloomfield et al. 2007), albeit in male soccer. It is also likely that female soccer players would predominately change direction during 0-45º ranges. Another consideration to make when conducting these cutting tasks is that they should be performed bilaterally, with previous epidemiological observations identifying between limb differences in injury incidence and injury types. However, the differences between female soccer playing ages during the completion of sidestep and crossover cutting manoeuvres have yet to be determined, thus future research is warranted.

There are other methodological concerns in relation to assessing biomechanical markers of knee ligament injury risk during the completion of cutting manoeuvres. In addition to the type of cutting manoeuvre, various approach speeds have been adopted during the assessment of knee biomechanics that range from 3-9m/s (Sigward and Powers, 2006; Landry et al. 2007; Ford et al. 2011 Ortiz et al. 2011; Vanrenterghem et al. 2012; Imwalle et al. 2013; Kristianslund and Krosshaug, 2013; Fox et al. 2017). As running velocity influences kinematic and kinetic parameters of the knee joint, it is also difficult to select an appropriate approach speed during cutting tasks. Although there is evidence to suggest that cutting tasks are associated with the incidence of knee ligament injuries (Brophy et al. 2014; Waldén et al. 2015), there is a lack of empirical evidence derived from biomechanical analyses. For instance, no study has quantified the relationship of biomechanical measures of the knee joint in relation to injury risk from prospective cohort studies (Sharir et al. 2016), where such observations are required when establishing injury risk factors (Bahr, 2016). There is also limited evidence that identified if cutting tasks can distinguish between those who are injured and injury free (Sharir et al. 2016). Although change of direction tasks are relevant to the movements associated with injury, the methods associated with change of direction tasks require further considerations in relation to screening for potential injury risk.

Hopping Manoeuvres

Where previous research has utilised sidestep and crossover cutting manoeuvres, they have typically done so with the use of a running approach prior to the change of direction (Besier et al. 2001; Landry et al. 2007; Greg, 2009; Haven and Sigward, 2014; Vanrenterghem et al. 2012; Sankey et al. 2015). Additional studies have adapted this method by incorporating a hopping approach prior to the change of direction task appreciate the mutiplanar mechanisms of knee ligament injuries (Rudolph et al. 2000; Ortiz et al. 2011). Such hopping tasks has identified significant differences between healthy controls and ACL reconstructed participants for sagittal and frontal plane knee biomechanics when including a change of direction component (Deneweth et al. 2010; Orishimo et al. 2010; Oberländer et al. 2012; Roos et al. 2014). Similar evidence for running based cutting manoeuvres are currently not available in literature, and as such, it is unclear if these tasks can differentiate between those with and without injury. Whilst the knee kinematics and kinetics exhibited during the completion of hopping tasks can differentiate between controls and previously injured participants, it is unclear whether these assessments can also make similar observations between those with varying levels of injury risk. When considering that female soccer players are predisposed to an increased risk of knee ligament injuries (Harmut et al. 2008; Waldén et al. 2011) with risk further enlarged in youths (Brophy et al. 2010; Hägglund and Waldén, 2015), significant differences in knee biomechanics may be identified between these cohorts of players. As such, hopping manoeuvres may identify exacerbated knee biomechanics in youth female soccer players when compared to senior aged players that may be associated with increased knee ligament injury risk.

Typically, biomechanical assessments of knee ligament injury risk are conducted without considering lower limb muscular strength. As previous literature has consistently identified that knee joint biomechanics and thigh musculature strength influences injury risk, such previous observations have not considered these factors jointly during injury risk screening. The lack of previous attempts for quantifying thigh musculature strength and knee joint biomechanics jointly may be due to that isokinetic dynamometry and 3D motion capture are different measurement tools. Nevertheless, the knee joint angles and velocities exhibited during isokinetic dynamometry may be used to subsequently inform the functional task used to quantify thigh musculature strength and knee biomechanics jointly. As such, based on previous observations, hopping manoeuvres appear to be an appropriate task to quantify thigh musculature strength since these movements are suggested to elicit similar knee angular velocities to those observed during isokinetic dynamometry (~200°·s^{-1}) (Wang, 2011) when compared to running at 3.5m/s (~500°·s^{-1}) (Ferber et al. 2003). In turn, using predetermined isokinetic strength data defined at specific joint angles and velocities, thigh musculature strength may be quantified during the completion of hopping tasks as a function of knee joint angle and velocity. These considerations would also be able to determine if the thigh musculature strength are suitably developed to dissipate the moments placed upon the knee joint, and could influence injury risk relative to female soccer playing age. Issues associated with screening should therefore consider the tasks and mechanisms that are associated with injury risk, and the demands of soccer in order to identify both discrepancies in strength and movement.

Determining Different Phases of Functional Movements

Biomechanical assessments typically report peak values exhibited during the sagittal and frontal planes of the knee joint (Hewett et al. 2005; Landry et al. 2007; Havens and Sigward, 2015). Previous studies have also typically focussed on the point of initial ground contact due to the reported association with knee ligament injury risk (Hewett and Myer, 2011; Norcross et al. 2013). By only considering the point of initial contact, these studies may disregard other important aspects of these tasks which may better indicate discrepancies in technique. Although functional movements encounter phases of eccentric and concentric muscular actions (De Villarreal et al. 2010; Komi, 2011), biomechanical parameters rarely refer to these loading and propulsive phases of movement. Negative and positive knee angular velocities have been suggested to estimate the eccentric and concentric phases of movement, respectively (Komi, 2011), and could be used to determine the loading and propulsive phases of functional tasks. As the demands of the KF and KE are increased during higher knee angular velocities, this may in turn negatively affect knee biomechanics during functional tasks. Determining sagittal and frontal plane knee biomechanics during the loading phase of functional movements are further justified when considering the thigh musculature are required to dissipate large impact forces and maintain postural control during this period (Shimokochi and Shultz, 2008; Boden et al. 2010; Podraza and White, 2010). Moreover, the propulsive phase of functional movements coincide with the period where multiplanar demands are highest, and likely to exhibit the largest knee abduction angles and moments (Quatman, Quatman-Yates and Hewett, 2010). These considerations may also be used to quantify thigh musculature strength values during at the aforementioned phases of hopping tasks. In turn, these approaches may be able to identify whether the moments placed upon the knee joint are disproportionate at specific phases of movement where injury risk is purportedly increased.

2.6 Summary of Literature

Epidemiological observations highlight that the reduction of KF and ACL injury risk in soccer players are of primary importance due to the prevalence and severity of these injuries, respectively. As KF and ACL injuries are also influenced by playing age and gender of the soccer player, potential injury risk of these cohorts of players should also be determined, especially as senior aged males have been afforded the most attention.

Aetiological factors associated with injury risk identifies previous injury as a key non-modifiable risk factor for future injuries, thus reiterating the importance of preventing primary injuries. The reduction of primary KF and ACL injuries are relative to playing age and gender, and is therefore non-modifiable. However, injury risk in these cohorts of players are suggested to be modifiable by the strength characteristics of the thigh musculature, along with associated discrepancies in knee biomechanics identified in females.

The criterion method of characterising thigh musculature strength is quantified through isokinetic dynamometry, but the associated procedures are performed at low testing velocities and disregard joint angle, thereby lacking functional relevance in both assessment and analysis. Procedures that determine thigh musculature strength should also be informed by kinematic analysis of functional movements that better resemble the mechanisms associated with injury.

CHAPTER 3

GENERAL METHODS

3.1 General Methods

Identification of Research Participants

Participants for all studies were male and female soccer players belonging to professional teams that included senior and youth playing ages. For the purposes of the thesis, youth players were defined between 15-19 years of age, whereas senior players were defined from ≥ 20 years of age who were all outfield players. The inclusion criteria specified that all participants were able to successfully complete familiarisation trials before participating in experimental trials. Inclusion criteria also specified participants were free of lower limb injury 6 months prior to data collection, but did not exclude those with previous injuries to satisfy statistical power. The inclusion criteria also specified that all players were required to complete a minimum of ≥5hr·week^{-1} of soccer specific activity. Participants were also removed from each respective study if they were allergic to tape, possessed cardiovascular or respiratory conditions and experienced pain or discomfort during any testing condition.

Ethical Considerations

All participants were informed of the associated risks with each study before providing written consent. Parent/guardian assent was also obtained for the youth players aged below 18 years of age and were present throughout all visits. The current study was also approved by a local university ethics committee and conformed to the Declaration of Helsinki. Prior to the start of each trial, all equipment was risk assessed and calibrated in accordance to the manufacturer's guidelines. The primary researcher possessed a clear DBS check through Edge Hill University.

Pre-Exercise Measurements

Prior to each experimental condition, all participants were required to complete a health screening procedure comprising a health, physical activity, and pre-exercise control questionnaire, and the measurement of resting heart rate and blood pressure. Values of >90 beats·min−1 and >140 mmHg/90 mmHg, respectively, were contraindications to exercise. Prior to each study, participants age (years), height (cm) and mass (kg) were measured and recorded using a wall-mounted stadiometer (Holtain, Harpenden HSK-BI, UK) and top pan scales (Seca, Germany).

Experimental Designs

Participants were required to attend the laboratory to complete familiarisation and experimental trials. In accordance with the participants regular training schedule, and in an attempt to control for circadian variation (Rae et al. 2015), all testing was conducted within participants typical training schedules. Participants attended the laboratory on each occasion in a 3hr post-absorptive state following a 48 hour abstinence of exercise factored into the respective team's microcycle and refrained from alcohol consumption. As previous observations have identified that isokinetic strength measures of the thigh musculature are consistent across different phases of the menstrual cycle (Gür et al. 1997; Abt et al. 2007; Gordan et al. 2013), the thesis therefore did not control for menstruation for female participants. Prior to the start of each trial, participants were also required to complete a standardised 5 minute warm-up on a stationary cycle ergometer (Monark, 824E, Sweden) at 60W. Data collection was conducted at the beginning of all participant's preseason to control for seasonal variation. All participants were instructed to wear appropriate attire for all studies and testing conditions. Female participants in Section B of the thesis were instructed to wear non-reflecting clothing to eliminate erroneous data from the infrared cameras.

No performance feedback was provided to participants during all experimental trials to account for research bias and/or external influences.

Isokinetic Dynamometry

Section A of the thesis utilised an isokinetic dynamometer (System 4, Biodex Medical Systems, Shirley, New York, USA) to bilaterally assess the strength characteristics of eccKF and conKE. For studies 1, 3 and 4, isokinetic testing velocities were conducted in the order of 180, 270 and $60^{o}{\cdot}s^{-1}$ for sufficient reliability (Greig, 2008) (ICC's: ≥ 0.76). In accordance with previous observations (Drouin et al. 2004), $270^{o}{\cdot}s^{-1}$ was selected as the highest testing velocity since the dynamometer lever arm was unable to reach the pre-set velocity. For study 2, 8 isokinetic testing velocities were used to characterise the force-velocity strength profile of eccKF and conKE in the order of 150, 180, 120, 210, 90, 240, 60 and $270^{o}{\cdot}s^{-1}$. This order of isokinetic speeds were implemented based on pilot data demonstrating angular velocities in ascending order elicited a fatigue response. For each lower limb, and at each angular velocity and contraction type, participants were instructed to perform three maximal contractions through their full range of movement. Passive knee flexion performed at $60^{o}{\cdot}s^{-1}$ separated each repetition and a rest period of 60s interspersed each set (Croisier et al. 2008). No performance feedback was provided due to the reported effects on isokinetic torque (Campenella et al. 2000). Verbal instructions were also not provided due to the potential extraneous influence on force production (Marchant and Greig, 2017). The range of motion of the knee joint was set at 25-90° (0° = full extension) with the anatomical reference set at 90°, and gravity corrected at 25° of knee flexion in accordance with the manufacturer's guidelines. Each participant was secured in a seated position with approximately 90º hip flexion where the eccKF musculature is able to exhibit the highest PT when compared to increased hip extension, and specific to the late swing phase of movement (Mohamed et al. 2002; Guex et al. 2013a, 2013b). In accordance with the manufacturers' guidelines, restraints were applied proximal to the knee joint across the thigh, waist and chest, with the cuff of the lever arm secured 3cm proximal to the malleoli. The foot was placed in a neutral position in accordance with manufacturer's guidelines, and based on previous observations that identified that thigh musculature activity and strength is not significantly influenced by foot position (McCaw and Melrose, 1999; Escamilla et al. 2001; Paoli et al. 2009). The lever arm alignment to the lateral femoral epicondyle was conducted in a position between knee extension and flexion to account for potential misalignment that can occur during the completion of the exercise.

Data Analysis

The isokinetic phase was identified at the constant angular velocity by applying a 1% cut-off. The PT and APT were identified, along with FR, was defined as the range over which 85% of PT was maintained. The PT values recorded from the eccKF and conKE assessments were used to calculate the DCR. The AST and DCR_{AST} were identified at 10° increments between 70 and 40°. The choice of angular range and 10° increments was based on the isokinetic data which was common across groups, contraction types and angular velocities that was identified with raw data. No smoothing of the raw data was undertaken since such analyses have only been used in ACL deficient participants (Czaplicki et al. 2015; Huang et al. 2017) who have been previously identified to possess irregular curves (Tsepis et al. 2004; Bryant et al. 2011). Moreover, previous work in healthy and soccer populations have not included smoothing algorithms (El-Askher et al. 2015; Cohen et al. 2015; Evangelidis et al. 2015; De Ste Croix et al. 2017) and may not be relevant or applicable for practitioners working with elite athletes.

Three-Dimensional Motion Capture

For section B of the thesis, 3D motion capture was used to biomechanically assess functional tasks. The trials comprised the completion of sidestep and crossover hopping manoeuvres (Figure 3.1) using a hopping approach prior to the change of direction task. Participants were instructed to unilaterally hop in a straight line on a predetermined limb over two 16cm hurdles to gather momentum. The third hop incorporated the change of direction component, where participants were required to land on a force-plate and perform a 45° cut over an additional hurdle. The 45° cutting angle was selected based on previous soccer match play notational data that identified the majority of change of direction tasks are commonly performed at such angles (Bloomfield et al. 2007). The participants were instructed to provide minimal ground contact time with each hop, in accordance with previous recommendations (Hamilton et al. 2008). In order to account for individual variation in height, the distance between each hurdle was standardised by the distance between the anterior superior iliac spine and lateral malleolus. The use of arm movements were prohibited to negate influences of the trunk and upper extremities on lower limb biomechanics (Hewett et al. 2010; Hewett and Myer, 2011; Frank et al. 2013). The direction of movement (sidestep or crossover) was instructed to participants prior to the commencement of each trial, with each instruction being delivered in a random order. In an attempt to eliminate the effects of fatigue, 60 seconds separated each hopping trial. Three hops for each lower limb and direction of manoeuvre were selected as the minimum number of trials to account for movement variation for all kinematic variables investigated (ICC's ≥ 0.73) (Mok et al. 2017). No performance feedback was provided through the experimental trial by the researcher to negate any external influences (Ford et al. 2015; Kiefer et al. 2015). Trials were repeated when participant lost balance during each trial and/or utilised arm movement to maintain postural control. In accordance with previous suggestions (Hamiltion et al. 2008), participants were allowed 1-3 practice attempts prior to data collection.

Figure 3.1 illustrates the sidestep (A) and crossover (B) cutting manoeuvre (Potter et al. 2014).

Calibration was completed prior to the start of each experimental trial using a dynamic wand (Wand length 502.5mm). The calibration was successful when the standard deviation of the wand length was below 2mm, in line with the manufacturer's guidelines. A static calibration frame was used to minimise the source of error from differences in marker placement. Participants were bilaterally fitted with 16 retro-reflective markers on the base of the first and fifth metatarsal, the lateral and medial malleoli, the lateral and medial femoral epicondyles, and over the anterior superior iliac spine and posterior superior iliac spine (Figure 3.2). Each reflective marker was placed directly onto the skin with double sided adhesive tape and further secured with hyperfix to further reduce artefact. These markers were recorded continuously at a sampling frequency of 120Hz via Qualisys Track Manager (QTM) and the associated 9 high-speed infrared ProReflex MCU1000 cameras (Qualisys, QTM, version 2.0.365, Sweden). Ground reaction force data was also recorded using a single force-platform (Bertec, 4060H, USA) at a sampling frequency of 960Hz.

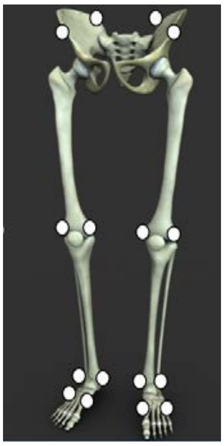

Figure 3.2 illustrates marker placements of the lower extremities.

Data Analysis

Following the completion of each trial, the kinetic and kinematic data were imported into Visual 3D software (Cmotion, California, USA), and processed for further analyses. This software was then used to model the pelvis, thigh, shank and foot. The model used a CODA (Charnwood Dynamics Ltd) pelvis orientation to define the hip joint centre (Bell et al. 1989). To control for variation in anatomical alignment, a 6 degrees of freedom kinematic model for each participant's local joint coordinates were aligned to neutral standing. Marker trajectories were filtered through a low-pass cut-off frequency of 12Hz in accordance with previous research that yielded acceptable reliability for functional tasks (ICC's ≥ 0.75) (Ford et al. 2007). The convention of kinetic and kinematic data identified knee flexion and knee adduction to be positive, whereas knee extension and knee abduction were negative. Moreover, the convention of knee adduction moments were also identified as positive, whereas abduction moments were negative. The contact phase with the force-plate was normalised to percentage of stance and was used for further analysis. The contact phase with the force-plate was identified when vertical ground reaction force exceeded 20N. Inverse dynamics were used to calculate peak knee extensor/flexor and adduction/abduction joint moments from motion and force data. The phases utilised for further analyses were peak values, initial contact (0.1 seconds following ground contact), loading and propulsive phases of the hopping manoeuvres. The loading and propulsive phases of functional movements were determined by calculating knee angular velocity, where negative and positive velocity provides an estimation of loading and propulsive phases of movement, respectively (Komi, 2011).

Data Analysis

To establish the reliability of data comprised within each experimental chapter, ICC's were calculated on all dependent variables. These calculations were performed on data collected during the experimental trials and on pilot data using the same participants identified in the experimental chapters. Pilot data was acquired by familiarising all participants to the experimental procedures, and following a minimum of 96 hours, participants completed the same testing conditions that replicated the experimental procedures. The data obtained following appropriate familiarisation was therefore used to ascertain the reliability of all dependent variables. In order to achieve sufficient statistical power (.0.8; $P \leq 0.05$), the dependent variable that elicited the highest number of participants was used for the study sample size. The ICC's performed in this thesis are interpreted as 0.2 = slight, 0.21–0.4 = fair, 0.41–0.6 = moderate, 0.61–0.8 = substantial, and .0.8 = almost perfect reliability (Landis and Coch, 1997). Further detail of additional statistical approaches used in this thesis can be located within the methods section of each experimental chapters where appropriate.

SECTION A

Angle and Velocity Specific Measures of Thigh Musculature Strength in Professional Male Soccer Players

Angle and Velocity Specific Measures of Thigh Musculature Strength during Anterior Cruciate Ligament Rehabilitation in Professional Soccer: An Explorative Case Study

Isokinetic Strength Differences Between Elite Senior and Youth Male Soccer Players

Isokinetic Strength Differences Between Elite Senior and Youth Female Soccer Players

Introduction

The prevalence and severity of KF and ACL injuries are a contemporary issue in elite soccer, and appear to be influenced by injury history, playing age and gender (LeGall et al. 2006, 2008; Harmut et al. 2008; Renstrom et al. 2008; Waldén et al. 2011; Ekstrand et al. 2011; Ekstrand et al. 2013; Hägglund et al. 2013; Waldén et al. 2013; Hägglund and Waldén, 2015; Ekstrand et al. 2016; Bahr, Clarsen and Ekstrand, 2017). It is suggested that strength deficits and imbalances of the thigh musculature are risk factors for KF and ACL injuries (Askling et al. 2003; Hewett et al. 2007; Croisier et al. 2008; Fousekis et al. 2011; Petersen et al. 2011; van der Horst et al. 2015; Augustsson and Ageberg, 2017; Attar et al. 2017; Lee et al. 2017), thus reinforcing the need to profile muscular strength. Isokinetic dynamometry that determines strength and imbalances of the thigh musculature are influenced by testing velocities and knee joint angles (Ashker et al. 2015; Cohen et al. 2015; Evangelidis et al. 2015; De Ste Croix et al. 2017), thus should be considered when determining strength in these cohorts of players.

Section A of the thesis comprises of four experimental studies focusing on isokinetic strength assessments of the eccKF and conKE at a range of testing velocities and knee joint angles. The first study is focused on determining the KF and KE strength characteristics across a range of knee joint angles and velocities in order to establish analysis metrics. The defined procedures and metrics of the first study will subsequently inform the following studies comprised within this Section. The second study observed the late stage ACL rehabilitation responses in a professional male soccer player, and compared to the cohort of players in the previous study at the point of return to play. The application of the defined procedures and metrics are designed to observe the modifiable nature of contemporary thigh musculature strength following prescribed rehabilitation, specific to knee joint angle and velocity. These procedures and metrics may also determine thigh musculature strength differences across soccer playing ages with pronounced differences in exposure to soccer-specific activity and conditioning. Therefore, studies 3 and 4 of the thesis compared the procedures and metrics used to quantify isokinetic strength of the eccKF and conKE between senior and youth soccer players, relative to gender. As injury risk is also increased in youth soccer players, relative to gender, these cohorts of players may demonstrate impaired isokinetic strength characteristics of the eccKF and conKE musculature when compared to their senior counterparts. The overall aim of Section A of the thesis is to further develop procedures and metrics associated with isokinetic strength assessments of the thigh musculature in elite soccer players that are sensitive to injury history, playing age and gender.

CHAPTER 4

Angle and Velocity Specific Measures of Thigh Musculature Strength in Professional Male Soccer Players

Parts of this chapter have been published in:

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4.1 Introduction

Epidemiological research into high-intensity intermittent team sports including soccer has consistently identified knee ligamentous and thigh muscular strain injuries to be most prevalent (Woods et al. 2004; Renstrom et al. 2008; Ekstrand, Hägglund and Waldén, 2011). These injuries can lead to large financial (Mather et al. 2013) and time loss implications (Waldén et al. 2016). Waldén et al. (2016) reported that only 65% of professional male players who sustained ACL injury were able return to previous competitive levels. The aetiology of knee ligamentous, KF and extensor muscular injury has consistently identified reduced muscle strength as a risk factor (Nielsen and Yde, 1989; Croisier et al. 2008; Lee et al. 2017).

The assessment of KF and KE strength is often conducted using isokinetic dynamometry (Greig, 2008; Lee et al. 2017; Van Dyk et al. 2016, 2017). However, literature to date has identified a limited association between injury incidence and the commonly utilised isokinetic indices of strength (Bennell et al. 1998; Sharir et al. 2016; Van Dyk et al. 2016). This lack of association might be attributed to the ways in which isokinetic strength characteristics are typically assessed and quantified. One of the most commonly utilised isokinetic metrics is that of peak torque (PT), which represents a single maximum to describe the torque-angle relationship at a predetermined velocity. This peak value negates an understanding of the sensitivity of strength to changes in angle, or how strength is maintained over the predetermined angular range. The angle of PT has been reported at ~70° (from full extension) during conKE contractions and ~35° for eccKF contractions in soccer players (Small et al. 2010). This lack of angular coincidence has led to the development of angle-specific derivations of dynamic strength ratios (El-Ashker et al. 2015; Evangelidis et al. 2015). The use of angle-specific torque (AST) data has been advocated more broadly, given the increased risk of musculature and ligamentous injury at extended knee joint angles (Boden and Dean, 2000; Olsen et al. 2004; Hewett and Myer, 2011; Chumanov et al. 2012; Higashihara et al. 2015). However, whilst angle-specific measures of isokinetic strength have been assessed in recreational and semi-professional soccer populations (Cohen et al. 2015; El-Ashker et al. 2015; Evangelidis et al. 2015), this profiling has not included professional players.

An additional metric often reported in isokinetic analyses defines 'work' as the integral of the torque-angle curve, which Dvir (2014) considered of little relevance given its strong correlation with PT and the influence of (predetermined and standardised) range of motion. However, the capacity to quantify the maintenance of strength throughout an angular range would have clinical relevance to determine strength values at functionally relevant knee joint angles. The predetermined angular velocity is also a methodological issue in isokinetic dynamometry, with assessments often conducted at low angular velocities of ≤ $120°\cdot s^{-1}$ (Small et al., 2010) representing limited functional relevance. Running and change of direction tasks associated with thigh musculature and knee ligament injuries are characterised by knee angular velocities of ~$400°\cdot s^{-1}$ (Nedergaard et al., 2014). Whilst the choice of angular velocity is ultimately limited by the dynamometer used, an inclusion of higher angular velocities is advocated (Greig, 2008).

When considering aetiological risk factors for lower limb injury in soccer, the current practices associated with isokinetic strength assessments may not be entirely suitable for identifying injury risk. Angle-specific strength assessments across a range of angular velocities may offer a better method of identifying strength deficits/imbalances specific to the injury mechanisms and, in turn, provide additional information pertinent to injury prevention strategies. With implications for current strength screening practices, the aim of this study was to assess traditional and novel isokinetic eccKF and conKE strength characteristics of professional male soccer players across a range of joint angles and angular velocities.

4.2 Methods

Participants

An a priori power calculation (G*Power 3.0.10) from pilot study data identified that a sample size of 26 was required to evaluate the interactions for all dependent variables (for statistical power .0.8; $P \leq 0.05$). A total of 26 professional male soccer players (age 26.19 ± 4.65 years; height 181.65 ± 5.71 cm; mass 82.19 ± 9.01 kg) was therefore recruited for the current study. The participants were all full-time professional soccer players competing in the English soccer League Two. Inclusion criteria specified that the participants demonstrated the capacity to complete a familiarisation trial specific to the experimental trial, were outfield players and were injury free for a minimum of 6 months prior to testing. In the two weeks prior to testing, the participants all completed training volumes of > 10 $h \cdot week^{-1}$ in addition to weekly friendly matches. The current study was conducted following an 8-week pre-season schedule, immediately prior to the commencement of the 2016-2017 season.

Statistical Analysis

To establish whether statistically significant differences existed between the senior and youth playing ages, a repeated measures general linear (GLM) was performed. The assumptions associated with a repeated GLM were assessed to ensure model adequacy. To assess residual normality for each dependant variable, q-q plots were generated using stacked standardised residuals. Scatterplots of the stacked unstandardised and standardised residuals were also utilised to assess the error of variance associated with the residuals. Mauchly's test of sphericity was also completed for all dependent variables, with a Greenhouse Geisser correction applied if the test was significant. Where significant main effects or interactions were observed, post hoc pairwise comparisons with a Bonferonni correction factor were applied with 95% CI for differences were also reported. Partial eta squared (η^2) values were calculated to estimate effect sizes for all significant main effects and interactions. Partial eta squared was classified as small (0.01 to 0.059), moderate (0.06 to 0.137) and large (>0.138) (Cohen, 1988). All statistical analysis was completed using PASW Statistics Editor 22.0 for windows (SPSS Inc, Chicago, USA). Statistical significance was set at $P \leq 0.05$.

4.3 Results

Peak Torque

Figure 4.1 summarises the relationship between PT and angular velocity for eccKF and conKE. The GLM did not identify an interaction for angular velocity, contraction, and limb ($P = 0.192$; $\eta^2 = 0.069$). There was however a significant contraction and angular velocity interaction ($P < 0.001$; $\eta^2 = 0.804$), with post-hoc analyses identifying significantly higher values recorded for the conKE (240.0 ± 31.6 Nm) data recorded at $60°\cdot s^{-1}$ when compared to the corresponding eccKF data (188.7 ± 27.2 Nm; 95%CI: 34.5 to 64.7 Nm; $P < 0.001$). Significantly higher eccKF (190.7 ± 43.8 Nm) data was also recorded at $270°\cdot s^{-1}$ when compared to the corresponding conKE data (166.7 ± 28.7 Nm; 95% CI: 9.9 to 33.9 Nm; $P = 0.001$). The ICC conKE PT at $60°\cdot s^{-1}$ (0.92), $180°\cdot s^{-1}$ (0.89), and $270°\cdot s^{-1}$ (0.81) were almost perfect. Likewise, the ICC values calculated for eccKF PT data recorded at $60°\cdot s^{-1}$ (0.86), $180°\cdot s^{-1}$ (0.83), and $270°\cdot s^{-1}$ (0.78) were substantial to almost perfect.

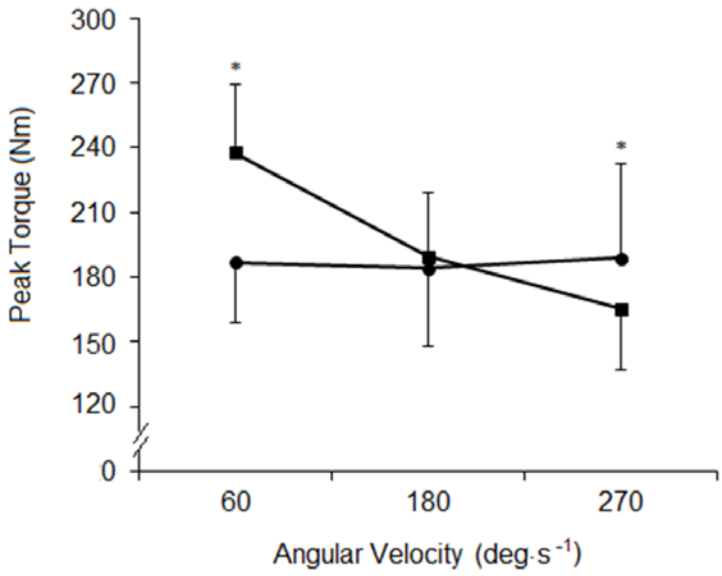

Figure 4.1 The influence of angular velocity on conKE (■) and eccKF (●) PT. * denotes significant difference between contraction types.

Angle of Peak Torque

The GLM did not identify interactions for contraction, angular velocity, and limb (P = 0.755; η^2 = 0.004). There was however a significant (P < 0.001; η^2 = 0.939) contraction and angular velocity interaction. Table 4.1 summarises the influence of angular velocity on APT, and identified that the eccKF and conKE PT occur at significantly different knee joint angles. The ICC conKE APT values calculated at 60°·s^{-1} (0.72), 180°·s^{-1} (0.70), and 270°·s^{-1} (0.67) were substantial. Likewise, the ICC values calculated eccKF APT data recorded at 60°·s^{-1} (0.71), 180°·s^{-1} (0.66), and 270°·s^{-1} (0.65) were also substantial.

Table 4.1 The influence of angular velocity and contraction type on APT. 95% CI for the significant interactions are also presented. * denotes significant difference with the corresponding data from the conKE contraction.

	eccKF APT (º)	conKE APT (º)	95%CI (º)
60°·s^{-1}	36 ± 9*	74 ± 6	34 to 42
180°·s^{-1}	35 ± 13*	71 ± 7	29 to 37
270°·s^{-1}	45 ± 14*	67 ± 7	16 to 25

Dynamic Control Ratio

The GLM identified no interaction for angular velocity and limb ($P = 0.070$; $\eta^2 = 0.109$). However, a significant main effect for limb was identified ($P = 0.018$; $\eta^2 = 0.220$), with significantly higher values recorded for the dominant limb (1.02 ± 0.06) when compared to the non-dominant limb (0.93 ± 0.20; 95%CI: 0.01 to 0.17). DCR also increased as a main effect for angular velocity ($P < 0.001$; $\eta^2 = 0.714$), with the DCR data recorded at 270°·s^{-1} (1.16 ± 0.25) being significantly higher than 180°·s^{-1} (0.98 ± 0.25; 95% CI: 0.10 to 0.25) and 60°·s^{-1} (0.79 ± 0.22; 95% CI: 0.26 to 0.46). The ICC values recorded at 60°·s^{-1} (0.84), 180°·s^{-1} (0.83), and 270°·s^{-1} (0.78) were substantial to almost perfect.

Functional Range

The influence of angular velocity and contraction on the FR is summarised in Figure 4.2. The GLM did not identify interactions for contraction, angular velocity, and limb ($P = 0.382$; $\eta^2 = 0.041$). There was however a significant ($P < 0.001$; $\eta^2 = 0.208$) contraction and angular velocity interaction, with significantly higher eccKF FR (27 ± 11º) data recorded at 60°·s^{-1} when compared to the corresponding conKE FR data (21 ± 8º; 95%CI: 2 to 10º; $P = 0.020$). Additionally, eccKF FR (22 ± 8º) data recorded at 270°·s^{-1} was significantly higher than conKE FR data recorded at the same angular velocity (12 ± 7º; 95%CI: 6 to 13º; $P = 0.020$). The ICC conKE FR values calculated at 60°·s^{-1} (0.86), 180°·s^{-1} (0.83), and 270°·s^{-1} (0.77) were substantial to almost perfect. Likewise, the ICC values calculated for eccKF FR data recorded at 60°·s^{-1} (0.84), 180°·s^{-1} (0.79), and 270°·s^{-1} (0.75) were also substantial to almost perfect.

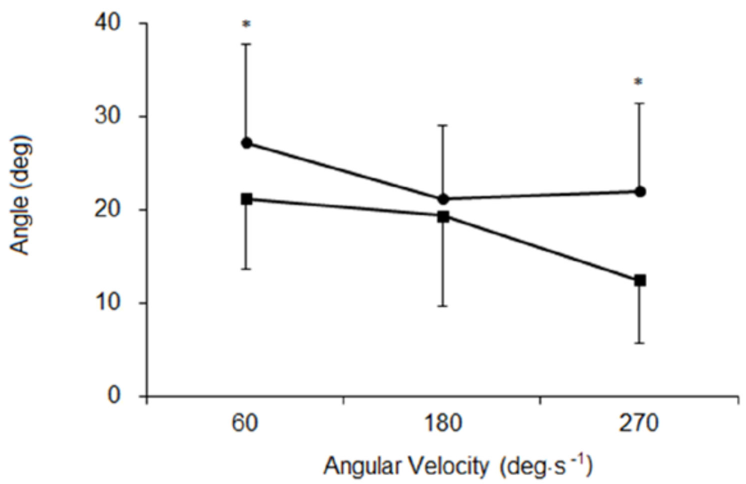

Figure 4.2 The influence of angular velocity on the FR (at 85% PT) in conKE (■) and eccKF (●). * denotes significant difference between contraction types.

Dynamic Control Ratio calculated from the AST data

Table 4.2 summarises the influence of limb dominance and DCR_{AST}. The GLM identified no interaction for limb, angular velocity and angle (P = 0.197; η^2 = 0.071), whereas a significant limb, angle interaction identified (P = 0.002; η^2 = 0.229). The ICC values calculated for the DCR_{AST} data recorded between 70 and 40° ranged between 0.88-0.79.

Table 4.2 The influence of limb and angle on the DCR_{AST} data. 95% CI for the significant differences are also presented. * denotes a significantly higher value when compared to the corresponding data in the contralateral limb.

Angle (º)	Dominant	Non-dominant
70	0.81 ± 0.23	0.82 ± 0.34
60	0.99 ± 0.21 *CI: 0.72 to 0.22	0.80 ± 0.16
50	1.24 ± 0.21 *CI: 0.03 to 0.30	1.03 ± 0.19
40	1.53 ± 0.32 *CI: 0.05 to 0.39	1.03 ± 0.19

Angle Specific Torque

Figure 4.3 summarises the influence of joint angle on the angle matched conKE and eccKF torque at each angular velocity. The GLM identified significant contraction, angular velocity, limb, angle (P = 0.001; η^2 = 0.297) interactions, as identified in Table 3.3. These data identify that conKE AST decreases with increased knee joint angle and velocity, whereas eccKF were significantly higher at matched angles. It was also identified that significantly higher eccKF AST for the dominant limb when compared to the non-dominant limb across specific knee joint angles and velocities. The ICC values calculated for the conKE AST data for all participants between 70 and 40° of knee flexion yielded substantial to almost perfect reliability (0.886-0.91). Likewise, the ICC values calculated for the eccKF AST data for all participants between 70 and 40° of knee flexion yielded substantial to almost perfect reliability (0.79-0.90).

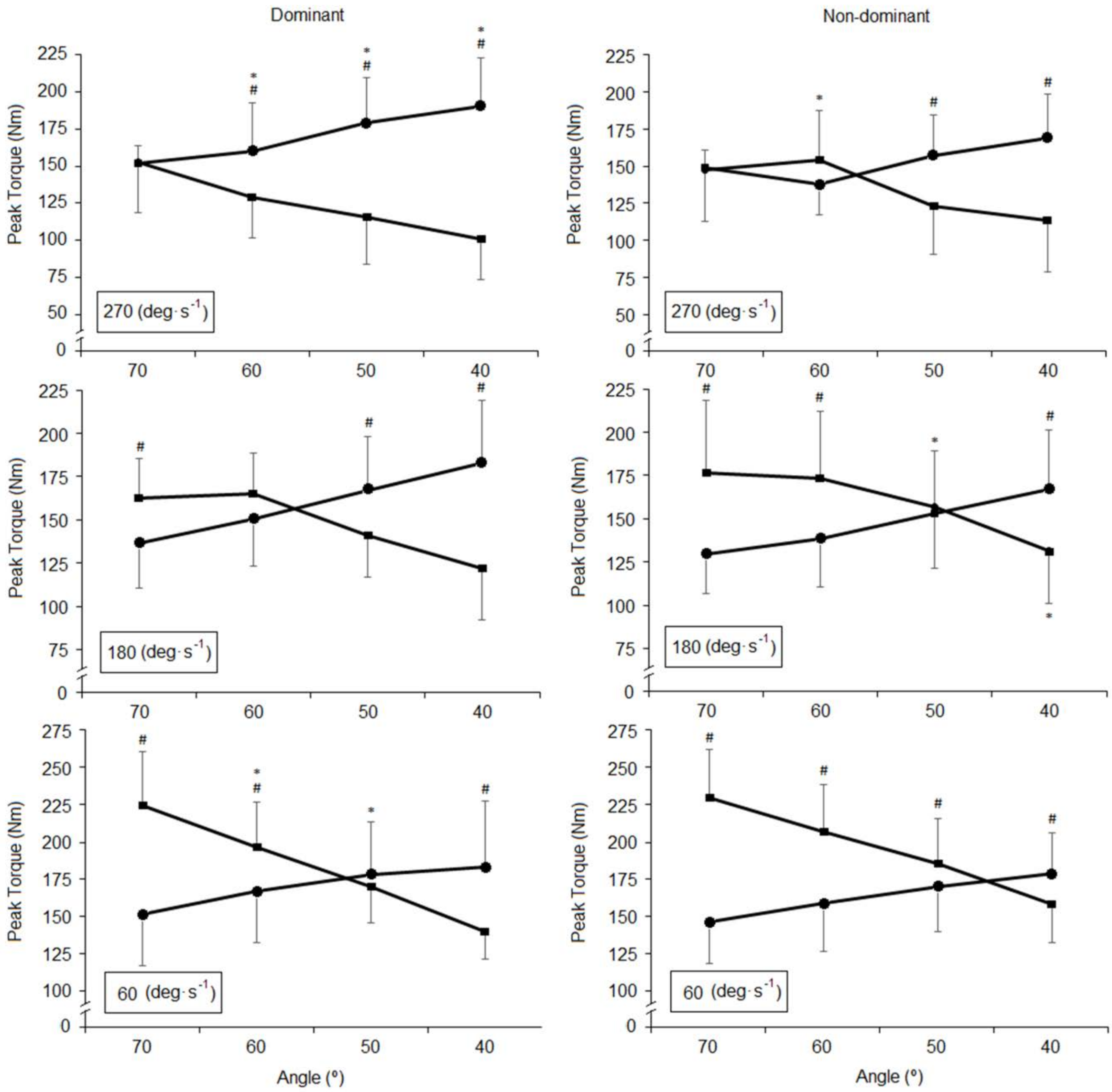

Figure 4.3 The influence of angular velocity on AST for conKE (■) and eccKF (●) * denotes significant difference between limbs. # denotes significant difference between contraction types.

Table 4.3 The influence of angular velocity, contraction type, limb and angle on the AST data. 95% CI for the significant differences are also presented.

Angular Velocity	Angle (º)	conKE (N.m) dominant	conKE (N.m) non-dominant	eccKF (N.m) dominant	eccKF (N.m) non-dominant
270°·s-1	70	160.7 ± 27.9	145.6 ± 34.3	152.3 ± 14.6	147.3 ± 10.8
	60	134.4 ± 20.3	152.7 ± 32.5	162.9 ± 33.9 #CI:11.9 to 45.2 *CI: 9.7 to 40.2	138.0 ± 25.0
	50	121.2 ± 29.0	122.5 ± 28.8	182.3 ± 33.8 #CI: 44.2 to 77.8 *CI: 9.4 to 39.5	162.9 ± 33.9 #CI: 18.4 to 52.0
	40	104.9 ± 26.6	112.5 ± 33.2	193.8 ± 35.6 #CI: 72.2 to 105.7 *CI: 7.5 to 41.7	169.3 ± 32.5 #CI: 38.7 to 74.8
180°·s-1	70	167.1 ± 18.5 #CI: 18.6 to 42.0	175.5 ± 35.6 #CI: 28.5 to 62.1	136.8 ± 26.2	130.2 ± 24.9
	60	163.8 ± 31.2	173.5 ± 39.4 #CI: 21.8 to 46.8	151.3 ± 27.5	139.2 ± 30.8
	50	140.3 ± 24.7	156.7 ± 32.6 *CI: 3.2 to 29.6	168.3 ± 32.3 #CI: 11.7 to 44.4	153.0 ± 34.2
	40	117.9 ± 24.0	132.1 ± 32.6 *CI: 1.46 to 26.9	185.2 ± 37.1 #CI: 80.9 to 83.6	168.5 ± 36.9 #CI: 25.2 to 47.5
60°·s-1	70	230.4 ± 35.3 #CI: 66.2 to 101.4	228.1 ± 33.8 #CI: 81.6 to 107.9	146.6 ± 27.6	140.2 ± 28.3
	60	200.2 ± 30.1 #CI: 26.4 to 49.1	202.0 ± 35.7 #CI: 41.1 to 68.0	166.4 ± 29.3	162.4 ± 30.3
	50	171.5 ± 24.2	177.8 ± 35.2	177.8 ± 34.2	175.5 ± 37.3
	40	140.7 ± 18.9	138.2 ± 20.0	184.8 ± 49.4 #CI: 24.4 to 63.6	177.8.8 ± 46.5 #CI: 11.8 to37.9

#denotes a significantly higher value when compared to the corresponding data from the other contraction type. *denotes a significantly higher value when compared to the corresponding data in the other limb.

4.4 Discussion

The primary aim of this study was to conduct a comprehensive isokinetic profile of the KF and KE in professional male players. The PT exhibited a significant contraction, angular velocity interaction; whilst eccKF strength was maintained, conKE strength decreased as a function of increasing angular velocity. The DCR was subsequently greatest at the highest angular velocity, with greater eccKF strength compared to conKE at angular velocities > $200°\cdot s^{-1}$. The eccKF also exhibited a significantly greater FR at the highest angular velocity. The FR is used to consider the shape of the strength curve, with a higher value indicative of a capacity to maintain ≥ 85% of PT (Croisier et al., 2008) across a broader range of motion. The FR was higher for the eccKF at all angular velocities, but exhibited a contraction, angular velocity interaction whereby range decreased with increasing angular velocity. Practitioners involved in injury screening should therefore consider a player's ability to maintain strength over a given range of motion (i.e. FR) at high angular velocities.

The DCR data also exhibited a main effect for limb, with higher values recorded for the dominant limb. There was however no difference between limbs for PT, thus supporting previous observations of no significant bilateral strength differences in elite soccer players (Fousekis, Tsepis and Vagenas, 2010; Daneshjoo et al., 2013). In contrast, the AST data were significantly higher in the dominant KF musculature, with more pronounced differences recorded at increased knee extension angles. Isokinetic profiling should therefore incorporate the analysis of AST data to identify potential bilateral asymmetries which may predispose players to greater risk of injury (Croisier et al. 2008; Kim and Hong, 2011). This is of particular importance given the influence of limb dominance on the incidence of KF injuries (Svensson et al., 2016).

The lack of influence of angular velocity on eccKF PT supports previous research (Rocha et al. 2011). In contrast, Greig (2008) reported increased eccKF PT with increasing angular velocity, attributed to lower torque values at slow angular velocities compared with the present study. This might reflect the calibre or training status of the players used. The increase in strength ratios with increased testing angular velocity is in agreement with previous research (Kellis, ArabatzI and Papadopoulos, 2003; De Ste Croix, Deighan and Armstrong, 2007; Hewett, Myer and Zazulak, 2008) and is attributed to decreased KE strength. Contrary findings have reported that the DCR decreases with increased knee extension (El-Ashker et al. 2015; Evangelidis et al. 2015), but these data were recorded closer to full extension where the ability to produce musculature force diminishes.

The current data recorded at high angular velocities and extended joint angles synonymous with lower limb injury risk demonstrate increased eccKF PT and FR when compared to the conKE contractions. The observed discrepancies in the eccKF and conKE PT data also results in an increased DCR_{AST} recorded at high angular velocities. In contrast, the current conKE strength data was however identified as being greater than the eccKF data but only during slow ($60°·s^{-1}$) angular velocities and at flexed knee positions (70º), where KF strain and knee ligamentous injury typically do not occur (Boden and Dean, 2000). It has previously been suggested that the risk of sustaining a KF strain or ligamentous injury is greater during high velocity movements during increased knee extension (Woods et al. 2004; Hägglund, Waldén, and Ekstrand, 2013; Kristianslund and Krosshaug, 2011). As such, the observed decrease in conKE strength at high angular velocities may therefore represent an aetiological risk factor. As such, this suggests that KE strength dominance in relation to the KF could be questioned as a risk factor for KF and ACL injury, particularly when considering the aetiological factors with these injuries (Hewett et al. 2007, 2010; Croisier et al. 2008; Lee et al. 2017).

Both KF and extensor musculature provide stability to the knee and ACL (Chmielewski et al. 2002; Hughes and Watkins, 2006), thus reducing anterior shear force and ACL injury risk (Doorenbosch and Harlaar, 2003; Kellis, ArabatzI and Papadopoulos, 2003). The KE musculature also helps to absorb shock and reduce strain during the initial ground contact from dynamic movements (Podraza and White, 2010). It can therefore be suggested that players need to possess sufficiently developed and balanced KF and extensor musculature to help cope with the demands of soccer-specific activity and reduce injury risk. The current data suggest that an increased emphasis should be placed on the development of high velocity conKE strength at increased knee extension angles.

The importance of considering a range of joint angles and angular velocities is apparent in the differences observed in the current APT data. Peak conKE torque was achieved at ~70º, whereas the eccKF torque was greatest at ~35º. The asynchrony observed in the APT data has implications for the traditional calculation of strength ratios derived from force magnitude alone (El-Ashker et al. 2015; Evangelidis et al. 2015), thus advocating the calculation of DCR_{AST}. The DCR_{AST} data recorded at $270°\cdot s^{-1}$ is comparable to values previously reported by Cohen et al. (2015) and Evangelidis et al. (2015). However, when comparing the DCR_{AST} at slow angular velocities, the professional players tested in the current study elicited increased eccKF strength when compared to their lesser standard counterparts (Cohen et al. 2015; Evangelidis et al. 2015). As a result, this increased DCR_{AST} values. The use of DCR_{AST} can therefore be used to differentiate between players of different playing standards, and also enable the calculation of strength ratios where ligamentous and muscular strain injuries are more likely to occur (Boden and Dean, 2000). For example, in the current study, the observed reductions in conKE torque at high angular velocities and extended knee angles resulted in an increased DCR_{AST}.

When considering that thigh musculature and knee ligamentous injuries typically occur in extended knee positions and at high angular velocities, practitioners should consider isokinetic testing protocols and metrics which consider these factors. The additional and novel metrics utilised in the current study may also aid practitioners in determining strength deficits associated with ipsilateral and bilateral muscular asymmetries. Improved isokinetic screening practices should also be used to inform training paradigms, developing specificity in strength and power adaptations aligned with the specific demands of soccer. Given gender differences in specific injury incidences, such as ACL injury (Hewett et al. 2010); the same profiling could be applied to female players. Youth players might also be a focus to further understand the longitudinal development of muscle imbalances in soccer players.

The use of isokinetic dynamometry imposes some inherent methodological issues, such as a restriction on obtaining isokinetic data close to full extension where injury risk is increased (Boden and Dean, 2000; Chumanov et al. 2012; Higashihara et al. 2015). The dynamometer constraints also do not allow data collection at angular velocities higher than those used in the current study and which might more closely represent the mechanisms of injury (Dowling et al. 2012; Nedergaard et al. 2014). Irrespective of the aforementioned limitations, isokinetic dynamometry and muscular strength testing is a common practice in soccer. It is therefore important for sports scientists and fitness coaches alike to identify the limitations of equipment, but as identified in the current study, practitioners should attempt to develop methods to better utilise equipment to further inform practice.

4.5 Conclusion

Professional soccer players were able to maintain eccKF strength over a range of angular velocities, but conKE strength decreased with angular velocity and increased knee extension angles. The influence of angular velocity has implications for the calculation of strength ratios and thus a range of angular velocities is advocated. The lack of coincidence in the peak of the torque-angle curves advocates the use of AST for determining thigh musculature strength. The FR was included as a novel isokinetic parameter which reflects the shape of the strength curve. The eccKF musculature was better able to retain 85% of PT over a greater angular range, which might serve as a protective mechanism for injury. The interaction of joint angle and angular velocity on the thigh musculature relationship may also have implications in injury screening in elite soccer players during the completion of rehabilitation, playing age and gender. Further research may wish to identify whether these additional parameters are sensitive to detect changes during rehabilitation in injured soccer populations, especially when considering the importance of sufficiently developed eccKF strength for providing support to the knee at knee joint angles associated with knee ligament injuries (Boden and Dean, 2000).

CHAPTER 5

Angle and Velocity Specific Measures of Thigh Musculature Strength during Anterior Cruciate Ligament Rehabilitation in Professional Soccer: An Explorative Case Study

Parts of this chapter are under review in the International Journal of Athletic Therapy and Training

5.1 Introduction

The first experimental chapter of the thesis identified that knee joint angle and velocity highly influence thigh musculature strength metrics in senior aged professional male soccer players. Specifically, with increased knee joint angular velocity, conKE strength diminished, whereas eccKF remained stable. Furthermore, conKE strength also diminished with increased knee extension angles, whereas the eccKF strength values increased. When considering that thigh musculature and knee ligament injury reportedly occur during increased knee angular velocities and extension, these findings do not reflect a conKE strength dominance which is a suggested risk factor for the aforementioned injuries. These procedures and metrics have yet to be considered in injured soccer players, and those with previous injuries. As such, it unclear if these procedures and metrics are able to identify differences between injured and non-injured soccer players. It is also unclear whether these metrics are sensitive to an acute bout of exercise during rehabilitation that may modify future injury risk.

A study in professional male soccer reported that only 65% of players who sustain ACL injury return to previous competitive levels three years after injury (Waldén et al. 2016). As such, primary ACL injuries increase the number of secondary injuries amongst professional soccer players and attributed to strength impairments of KF and KE musculature at the point of return to play (Schmitt et al. 2015; Kryitsis et al. 2016). Given the functional role in stabilising the knee (Kellis et al. 2003; Hughes and Watkins, 2006), adaptation of the KF and KE musculature during rehabilitation is of primary importance.

Isokinetic assessments of concentric KF and KE strength are used to identify rehabilitation responses and bilateral asymmetry at the point of return to play (Thomas et al. 2013; Czaplicki et al. 2015). However, failure to consider the DCR (Aagaard et al. 1998) and slow testing velocities in relation to injury mechanism limits functional interpretation. Specifically, ACL injury risk is associated with lower DCR's that indicate higher KE strength relative to the KF musculature, thereby increasing ACL strain (Olsen et al. 2005; Grimdem et al. 2016). When also considering functional movements associated with ACL injury (Nedergaard et al. 2014) exhibit knee angular velocities that resemble the higher isokinetic testing velocities, and may enhance the functional relevance of isokinetic strength assessments. Furthermore, whilst isokinetic assessment of KF and KE strength is common within professional soccer (Croisier et al. 2008) the sole use of DCR fails to consider that KF and KE PT occur at different knee joint angles (Small et al. 2010; De Ste Croix et al. 2017). When considering the injury mechanisms associated with ACL injury (Boden and Dean, 2000; Hsiao et al. 2014), angle-specific strength measures should be considered at relevant knee extension angles and angular velocities as previously identified in the previous experimental chapter.

A common return to play criteria in professional soccer assesses bilateral strength asymmetry of both the injured and non-injured lower limbs, where values less than 10% are considered acceptable (Grimdem et al. 2016). However, following a prolonged rehabilitation period, the detrained and atrophied non-injured limb may not represent a suitable control. Therefore, a healthy control group should be used to identify whether strength deficits exist in injured populations (Hsiao et al. 2014). Return to play guidelines also suggest KE strength asymmetries greater than 10% and returning to play before 9 months postoperative surgery are significant predictors of ACL re-injury (Grimdem et al. 2016), thus reiterating the importance of sufficient rehabilitation. The primary aim of this study was to observe changes in a professional soccer player's isokinetic bilateral strength at varying angular velocities during late stage rehabilitation from ACL reconstructive surgery. A secondary aim of this study was to compare the case to a group of 26 non-injured players (from previous study) when their club decided the point of return to play. The final aim of this study was to consider both angle-specific and non-angle-specific strength ratios at the point of return to play. In relation to the aims of the thesis, the aims were to also assess if the procedures and metrics identified in the previous experimental study are modifiable and sensitive to compare injured and non-injured soccer cohort of players.

5.2 Case Presentation

Patient

The case was a 26 year-old professional male soccer player (height: 184.50cm; mass: 84.50 kg) from the English Football League Division Two. The injury occurred in January 2016 during a contact situation where the case collided with an opponent attempting a tackle, injuring the dominant right lower limb (defined as the preferred kicking limb). The present injury occurred during the first 15 minutes of a match. The ACL injury was confirmed by a magnetic resonance imaging scan, revealing a grade III tear. Surgical reconstruction of the right ACL was performed via patella tendon graft 7 weeks after injury. An injury also occurred to the medial collateral ligament (MCL) with a grade III tear to the right lower limb ~5 months prior to the present injury. The case has also previously injured their left ACL ~8 years prior to the present injury. A hamstring tendon was used to reconstruct their left ACL.

The *M* value quantified the slope of the force-velocity curve by each PT value for eccKF and conKE contractions across angular velocities. The *M* value calculated the direction of the force-velocity curve of eccKF and conKE through the change of PT relative to angular velocity, where a greater value represents a steeper slope. Strength ratios were defined as the DCR derived from the peak eccKF and conKE values, and DCR_{AST} at 40º knee flexion. A rehabilitation response was determined by comparing the data recorded for both the treatment and uninvolved limbs across weeks of the rehabilitation. The within-subject standard deviation for all four assessments were used to calculate standard error of measurement (SEM) (Bland and Altman, 1996) for rehabilitation responses where changes greater than SEM were attributed to meaningful change (Mchorney et al. 1995). To determine a treatment effect, the data recorded from the initial assessment (week 18) was compared to that at the point where the club decided the player was returning to play (week 24). Where appropriate, both the rehabilitation and treatment effects were quantified using both absolute and relative differences.

In addition to the aforementioned analyses, the final isokinetic strength assessment (week 24) was compared to a control group of 26 male soccer players belonging to the same soccer team identified in the previous experimental study (age 26.19 ± 4.65 years; height 181.65 ± 5.71 cm; mass 82.19 ± 9.01 kg) who were injury free ≥ 6 months, prior to data collection. All players within the control group had no previous history of surgery or trauma to the knee. The control group were selected from the same team to control for different training and completed isokinetic bilateral strength assessments of eccKF and conKE at 180, 270 and 60°·s^{-1} where PT and DCR were identified. The control group data comprised average PT, and the DCR data recorded from isokinetic bilateral strength assessments of the eccKF and conKE musculature.

Comparative Outcomes

Table 5.1 and 5.2 identifies the stage rehabilitation responses for the uninvolved limb and treatment limb during the assessment period, with Table 5.3 depicting the overall treatment effect during the rehabilitation period. Concerning the rehabilitation responses, bilateral PT discrepancies were identified for both the eccKF and conKE musculature at the initial assessment, with larger discrepancies identified for the conKE PT data. The bilateral differences were dependent on the biweekly assessment; however, at week 24, the differences in the eccKF PT (< 7.3Nm) across all angular velocities were 4%. In contrast, the bilateral differences in the conKE data recorded at week 24 across all angular velocities were 16%.

In relation to the treatment effect, meaningful changes greater than SEM (PT: < 30.2Nm; APT: < 23°) were identified for the eccKF PT and APT data recorded at 90-270°·s-1 for the non-involved limb. A similar response was also observed for the treatment limb's eccKF PT and APT data with meaningful changes also being identified at angular velocities of 60-240°·s^{-1}. The treatment limb also demonstrated meaningful changes greater than SEM (< 23.5Nm) for conKE PT data recorded at angular velocities between 60-90°·s^{-1} and 150-270°·s^{-1}, but not for data recorded at 120°·s^{-1}. The APT data recorded for the treatment limb's conKE data also identified a meaningful effect (SEM: < 7°) at all angular velocities with the exception of both 120 and 240°·s^{-1}. In contrast to the other data, the change in the conKE PT and ATP data recorded for the non-involved limb were lower than the SEMs. In relation to the additional analyses, it was also identified that the eccKF and conKE slopes (as determined by the *M* values) decreased and increased respectively during the rehabilitation period.

When the case returned to play, PT and DCR were compared to a control group, and illustrated in Figure 5.1. At the point of return to play, the conKE PT data recorded for the non-involved limb was within 10% of that elicited from the control group. The conKE PT data recorded for the treatment limb was substantially lower when compared control group (Figure 5.1). As identified in Figure 5.1, the eccKF PT data recorded across both of the case's limbs were similar to the controls. Due to the observed strength deficits in the conKE musculature, the DCR for the treatment limb was greater than both the control limb and control group (Figure 4.2). Table 4.4 identifies differences between the DCR and DCR_{AST} data, with increased DCR_{AST} (40° knee flexion) between control and treatment limbs.

Table 5.1: The rehabilitation responses of the PT, APT, and *M* data recorded for the eccKF musculature of the uninvolved and treatment limbs. The bilateral differences for the biweekly assessments are also presented, with a positive value representing a higher value for the treatment limb.

		Angular velocity																
		60° ·s⁻¹		90° ·s⁻¹		120° ·s⁻¹		150° ·s⁻¹		180° ·s⁻¹		210° ·s⁻¹		240° ·s⁻¹		270° ·s⁻¹		
		PT (Nm)	APT (°)	PT (Nm)	APT (°)	PT (Nm)	APT (°)	PT (Nm)	APT (°)	PT (Nm)	APT (°)	PT (Nm)	APT (°)	PT (Nm)	APT (°)	PT (Nm)	APT (°)	*M*
Week 18	Uninvolved limb	133.0	33	136.4	43	152.6	30	171.1	31	162.7	36	136.8	55	138.3	72	153	67	0.10
	Treatment limb	114.9	52	135.3	43	133.8	46	132.2	68	125.4	49	141.6	48	142.9	77	155.9	75	0.08
	Bilateral difference	-18.1	19	-1.1	0	-18.8	16	-38.9	37	-37.3	13	4.8	-7	4.6	5	2.9	8	-0.02
	Asymmetry (%)	-14		-1		-12		-23		-23		-4		-3		-2		
Week 20	Uninvolved limb	113.4	28	78	51	123.4	37	122.7	46	121.1	36	106.6	70	121.5	66	115.4	57	0.01
	Treatment limb	169.8	34	154.6	34	157.8	35	135.7	39	147.9	37	147.3	38	151.6	40	146.4	70	0.11
	Bilateral difference	56.4	6	76.6	-17	34.4	-2	13.0	-7	26.8	1	40.7	-32	30.1	-26	31.0	13	0.10
	Asymmetry (%)	33		50		28		11		22		38		25		27		
Week 22	Uninvolved limb	156.9	38	150.2	29	151.9	37	147.8	36	152.0	31	146.9	37	149	77	155.8	71	0.01
	Treatment limb	159.2	36	161.8	33	157.8	41	145.6	37	150.8	38	156.2	73	153.1	80	163.4	76	0.02
	Bilateral difference	2.3	-2	11.6	4	5.9	4	-2.2	1	-1.2	7	9.3	36	4.1	3	7.6	5	0.01
	Asymmetry (%)	1		8		4		-1		-1		6		3		5		
Week 24	Uninvolved limb	177.9	29	187.1	34	183.5	32	178.3	33	185.1	33	180.3	33	172.6	35	178.4	43	0.00
	Treatment limb	185.2	30	184.6	29	185.2	32	184.8	33	184.3	32	177.6	34	179.1	36	177.4	78	0.04
	Bilateral difference	7.3	1	-2.5	-5	1.7	0	6.5	0	-0.8	-1	-2.7	1	6.5	1	-1.0	35	0.04
	Asymmetry (%)	4		-1		1		4		0		-1		4		-1		
	SEM	30.2	10	20.4	6	21.0	6	24.2	16	24.3	7	15.8	18	15.6	23	13.1	13	

Table 5.2: The rehabilitation responses of the PT, APT, and *M* data recorded for the conKE musculature of the uninvolved and treatment limbs. The bilateral differences for the biweekly assessments are also presented, with a positive value representing a higher value for the treatment limb.

		Angular velocity																
		60° ·s⁻¹		**90° ·s⁻¹**		**120° ·s⁻¹**		**150° ·s⁻¹**		**180° ·s⁻¹**		**210° ·s⁻¹**		**240° ·s⁻¹**		**270° ·s⁻¹**		
		PT (Nm)	**APT (°)**	**PT (Nm)**	**APT (°)**	**PT (Nm)**	**APT (°)**	**PT (Nm)**	**APT (°)**	**PT (Nm)**	**APT (°)**	**PT (Nm)**	**APT (°)**	**PT (Nm)**	**APT (°)**	**PT (Nm)**	**APT (°)**	***M***
Week 18	Uninvolved limb	230.2	81	211.1	72	197.3	80	176.7	77	184.0	73	177.1	70	160.3	67	140.8	62	0.43
	Treatment limb	132.2	80	129.8	70	125.2	78	108.1	72	112.1	72	100.9	66	102.5	67	91.9	67	0.19
	Bilateral difference	-98.0	-1	-81.3	-2	-72.1	-2	-68.6	-5	-71.9	-1	-76.2	-4	-57.8	0	-48.9	5	-0.24
	Asymmetry (%)	-43		-39		-37		-39		-39		-43		-36		-35		
Week 20	Uninvolved limb	200.6	74	176.1	78	175.9	76	162.9	73	167.2	69	154.7	65	134.5	61	127.7	58	0.35
	Treatment limb	156.8	82	157.7	75	146.2	68	125.0	78	133.0	73	132.5	72	124.6	73	118.5	67	0.18
	Bilateral difference	-43.8	8	-18.4	-3	-29.7	-8	-37.9	5	-34.2	4	-22.2	7	-9.9	12	-9.2	9	-0.17
	Asymmetry (%)	-22		-10		-17		-23		-20		-14		-7		-7		
Week 22	Uninvolved limb	213.0	80	193.4	70	183.5	75	189.4	72	182.2	68	170.4	68	153.4	64	161.8	66	0.24
	Treatment limb	163.1	83	150.5	75	139.7	69	124.1	78	122.9	73	123.3	73	118.1	63	107.5	64	0.27
	Bilateral difference	-49.9	3	-42.9	5	-43.8	-6	-65.3	6	-59.3	5	-47.1	5	-35.3	-1	-54.3	-2	0.03
	Asymmetry (%)	-23		-22		-24		-34		-33		-28		-23		-34		
Week 24	Uninvolved limb	222.2	71	206.8	68	204.2	74	182.4	76	184.6	69	181.2	66	177.8	64	157.6	60	0.31
	Treatment limb	185.6	83	178.0	77	161.0	82	163.4	75	156.8	74	149.4	75	150.1	67	138.3	83	0.23
	Bilateral difference	-36.6	12	-28.8	9	-43.2	8	-19.0	-1	-27.8	5	-31.8	9	-27.7	3	-19.3	23	-0.08
	Asymmetry (%)	-16		-14		-21		-10		-15		-18		-16		-12		
	SEM	22.0	1	19.9	3	23.5	7	14.9	3	8.5	1	20.2	4	19.8	4	19.5	3	

Table 5. 3: The treatment effect for the PT and APT data recorded for the eccKF and conKE musculature of the uninvolved and treatment limbs. A negative PT value indicates a reduction during the 6 week period. A negative APT value indicates a change towards more extended knee angle.

eccKF	Angular velocity															
	60° ·s-1		90° ·s-1		120° ·s-1		150° ·s-1		180° ·s-1		210° ·s-1		240° ·s-1		270° ·s-1	
	PT (Nm)	APT (°)	PT (Nm)	APT (°)	PT (Nm)	APT (°)	PT (Nm)	APT (°)	PT (Nm)	APT (°)	PT (Nm)	APT (°)	PT (Nm)	APT (°)	PT (Nm)	APT (°)
Treatment effect uninvolved limb	44.9	-4	50.7	-9	30.9	2	7.2	2	22.4	-3	43.5	-22	34.3	-37	25.4	-24
Treatment effect treatment limb	70.3	-22	49.3	-14	51.4	-14	52.6	-35	58.9	-17	36	-14	36.2	-41	21.5	3
Treatment effect uninvolved limb (%)	25		27		17		4		12		24		20		14	
Treatment effect treatment limb (%)	38		27		28		28		32		20		20		12	
SEM	30.2	10	20.4	6	21	6	24.2	16	24.3	7	15.8	18	15.6	23	13.1	13

conKE	Angular velocity															
	60° ·s-1		90° ·s-1		120° ·s-1		150° ·s-1		180° ·s-1		210° ·s-1		240° ·s-1		270° ·s-1	
	PT (Nm)	APT (°)	PT (Nm)	APT (°)	PT (Nm)	APT (°)	PT (Nm)	APT (°)	PT (Nm)	APT (°)	PT (Nm)	APT (°)	PT (Nm)	APT (°)	PT (Nm)	APT (°)
Treatment effect uninvolved limb	-8.0	-10	-4.3	-4	6.9	-6	5.7	-1	0.6	-4	4.1	-4	17.5	-3	16.8	-2
Treatment effect treatment limb	53.4	3	48.2	7	35.8	4	55.3	3	44.7	2	48.5	11	47.6	0	46.4	16
Treatment effect uninvolved limb (%)	-2		-3		-4		-1		-4		-4		-3		-2	
Treatment effect treatment limb (%)	29		27		22		34		29		32		32		34	
SEM	22	1	19.9	3	23.5	7	14.9	3	8.5	1	20.2	4	19.8	4	19.5	3

Table 5.4. Angle specific and non-angle specific strength ratios recorded across all angular velocities at the point of return to play

		Angular velocities							
		60°·s⁻¹	90°·s⁻¹	120°·s⁻¹	150°·s⁻¹	180°·s⁻¹	210°·s⁻¹	240°·s⁻¹	270°·s⁻¹
Week 24	Uninvolved limb eccKF:conKE ratio	0.80	0.90	0.90	0.98	1.00	1.00	0.97	1.13
	Uninvolved limb angle specific eccKF:conKE ratio	1.89	1.26	1.55	1.45	1.61	1.27	1.20	1.37
	Treatment limb eccKF:conKE ratio	1.00	1.04	1.15	1.13	1.00	1.19	1.19	1.28
	Treatment angle specific eccKF:conKE ratio	1.88	1.97	1.68	1.40	1.38	2.07	1.93	1.75

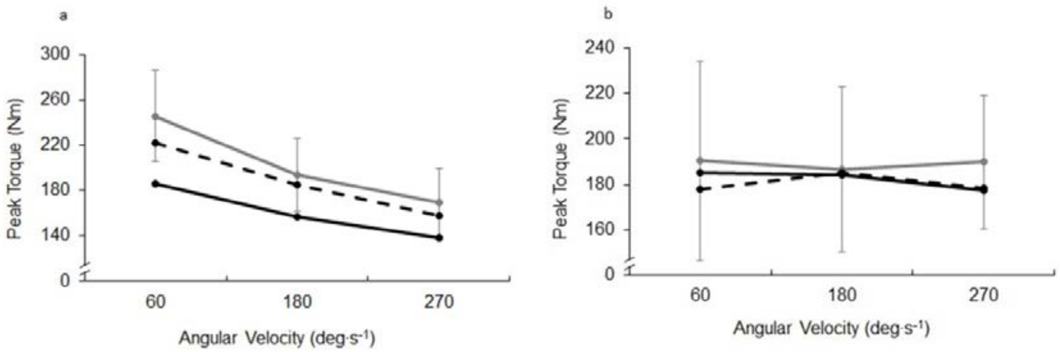

Figure 5.1 Isokinetic peak torque of conKE (a) and eccKF (b) at 60, 180 and 270°·s⁻¹ for uninvolved limb (— ● —), treatment limb (—●—) of present case and control group (—●—) at return to play.

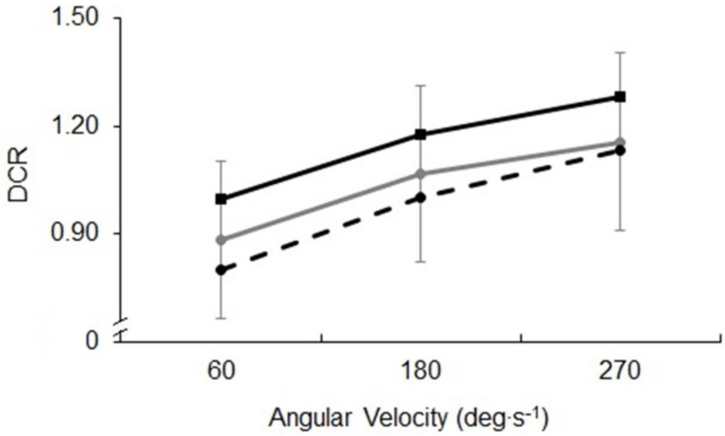

Figure 5.2 The dynamic control ratio at 60, 180 and 270º·s^{-1} for uninvolved limb (– • –), treatment limb (—•—) of present case and control group (—•—) at return to play.

5.3 Discussion

This is the first study to explore angle-specific measures of eccKF and conKE at varying angular velocities during late stage ACL rehabilitation in a professional soccer player. The primary findings demonstrate the magnitude of PT increases during rehabilitation for the uninvolved and treatment lower limb across angular velocities. At return to play, eccKF PT of both lower limbs demonstrated no strength asymmetries; however, bilateral asymmetries were identified for the conKE data, thus predisposing the player to increased re-injury risk (Grimdem et al. 2016). Moreover, differences were identified between the case's conKE data from the control group.

Typically practitioners identify strength asymmetries between injured and non-injured limbs, forming part of return to play criteria (Grimdem et al. 2016). However, the use of bilateral asymmetries are not entirely appropriate as detraining effects can also occur in a non-injured limb (Thomas et al. 2013) In relation to the first aim, at week 18 large bilateral differences were observed across all angular velocities for both the eccKF and conKE musculature. The bilateral differences did fluctuate throughout the rehabilitation period; however, lower bilateral differences were consistently identified for the eccKF data. The conKE data however elicited a response whereby the bilateral differences were consistently greater than those associated with the eccKF data, and at the final assessment, the observed differences were greater than the 10%. When considering the role of the KE musculature in relation to knee stability (Kellis et al. 2003) these data therefore suggest that at the point of return to play, the player may be at an increased risk of re-injury (Schmitt et al. 2015; Grimdem et al. 2016 Kyritsis et al. 2016). Consequently, practitioners should monitor and focus on restoring conKE strength after an ACL injury, especially when considering that the current rehabilitation programme appears to be insufficient to develop the PT of the conKE musculature. It should however be acknowledged that for the current case, the club deemed the player to be ready to return to play even with the knowledge of these data.

When considering the previous criticisms of bilateral comparisons to inform return to play decisions (Thomas et al. 2013) an alternative method is to compare the data recorded from the injured player to that of a non-injured control group. This was considered in relation to the second aim of the study, with the conKE and eccKF PT data recorded for both limbs being within the range of the control group, but not for the involved conKE musculature. These findings therefore reiterate that the present case's conKE strength was not sufficiently conditioned at the point of return to play. Moreover, DCR was considerably larger for the treatment limb when compared to both the uninvolved limb and the control group's data. This response is a result of the impaired conKE musculature identified at the point of return to play, and further advocates the use of a number of strength characteristics to determine a player's readiness to return to play. Furthermore, when considering the aforementioned bilateral differences identified across the rehabilitation period, these data also support the use of a number of methods to inform return to play decisions.

The rehabilitation responses for the treatment limb identified large changes in PT for both the eccKF and conKE musculature at all angular velocities, with direct influence on the force velocity slopes. As such, although the *M* value increased for the conKE data of the treatment limb, the observed change in the slope was small due to the somewhat similar upwards shift in torque identified for all testing velocities. The slope of the eccKF PT recorded across the angular velocities decreased during the rehabilitation period for both lower limbs. As such, the eccKF slope at the point of return to play better resembled that previously observed in non-injured players, whereby more consistent PT is observed across all testing velocities (Rocha et al. 2011). These novel findings suggest that the force-velocity slope is modifiable through rehabilitation and training, with this response being relative to both the muscle group and contraction type. These data therefore have potential implication for exercise prescription and training adaptation monitoring.

Although the changes in conKE APT were variable in both lower limbs during the assessment period, APT of eccKF demonstrated large changes with greater force production at increased knee extension angles. The observed shift of eccKF PT towards increased knee extension suggests that the KF musculature may better conditioned to stabilise the joint at angles associated with ACL injury (Boden and Dean, 2000; Olsen et al. 2005) These data therefore identify the importance of including a number of isokinetic metrics when analysing training induced changes in strength characteristics.

The calculation of DCR is typically performed using PT data without consideration that eccKF and conKE peak at different knee joint angles (Small et al. 2010). These ratios therefore negate consideration of angle matched torques, and also the consideration of ipsilateral imbalances in an extended position, where ACL injuries have previously been identified to most likely occur (Boden and Dean, 2000; Olsen et al. 2005). Previous studies have therefore attempted to assess DCR_{AST} in soccer players, with a consensus that these players typically possess increased eccKF torque towards more extended knee angles when compared to the conKE musculature (Cohen et al. 2015; Evangelidis et al. 2015). This is supported by the current data, whereby DCR_{AST} values were notably higher in the treatment limb, as a result of impaired conKE torque at increased knee extension angles across all testing velocities. These data therefore reiterate the importance of ensuring the conKE musculature possesses sufficient strength at more extended knee angles, and raises questions about the use of non-angle specific strength ratios as a means of determining return to play.

In addition to the limitations of isokinetic dynamometry, as previously identified, there are further limitations associated with this study. As this present case did not obtain strength measurements prior to reconstructive surgery, comparisons cannot be made to baseline measures and must be acknowledged as a limitation. Moreover, since the present case had an MCL in the ipsilateral knee prior to the current ACL injury, it was not possible to control for prior injury. The current ACL injury occurred in a contact situation, which may involve different aetiological factors for injury compared to non-contact injuries.

5.4 Conclusion

This present study provides insight into how eccKF and conKE adapt to late stage ACL rehabilitation in a professional male soccer player. The treated limb's eccKF PT and M values were similar to the uninvolved limb and control group, whereas conKE PT were substantially different in the treatment limb when compared to controls. Practitioners should be aware of the potential implications of patients prematurely returning to play and achieving bilateral strength asymmetries below 10% as suggested by previous literature. As it was identified that angle and velocity specific measures of eccKF and conKE strength were modified during acute bouts of exercise during rehabilitation is indicative of a reduced injury risk. However, as the review of literature identified youth male soccer players are predisposed to an increased risk of injury when compared to senior aged players, there appears a need to consider these procedures and metrics in different age groups.

CHAPTER 6

Isokinetic Strength Differences Between Elite Senior and Youth Male Soccer Players

Parts of this chapter are published in the Journal of Strength and Conditioning Research, in press.

6.1 Introduction

The previous experimental chapter identified that the traditional PT data and their associated DCR values, including their angle-specific derivatives, were sensitive to injury status, and modifiable through an appropriate training stimulus. As the previous experimental chapter demonstrates that the procedures and metrics proposed by this thesis are modifiable following an acute bout of exercise, responses over a prolonged period of time may also be observed. Since youth soccer players are predisposed to an increased injury risk when compared to their male counterparts, prolonged periods of soccer specific exercise may adapt the strength profiles in senior aged soccer players, thereby modifying and potentially reducing injury risk. Differences in thigh musculature strength between senior and youth soccer players may consequently influence injury risk in younger players.

Epidemiology studies in professional soccer have reported thigh musculature strains to be prevalent in both male professional (Ekstrand et al. 2011, 2013) and youth soccer players (LeGall et al. 2008; Renshaw and Goodwin, 2016). When compared to their senior counterparts, there appears to exist a greater proportion of thigh musculature injuries in youth players (LeGall et al. 2006) specifically between 16-18 years of age (Renshaw and Goodwin, 2016) and particularly in players following adolescent growth (Van Der Sluis et al. 2015). Given the specific injury epidemiology and potential influence of adolescent growth, strength deficits in elite youth soccer players have implications for performance and injury (Kellis et al. 2001; Croisier et al. 2008). In support, it has been suggested that strength of the thigh musculature is a modifiable risk factor in preventing muscular strains in soccer (Askling et al. 2003; Croisier et al. 2008), thus identifying the strength training needs of elite youth soccer players would inform the development of effective strength and conditioning interventions. As such, it appears that training history and training exposure may also influence thigh musculature strength and potential injury risk (De Ste Croix et al. 2002, Cloke et al 2012). Considering that weekly training load increases in youth soccer players with playing age (Wrigley et al. 2012), practitioners therefore need to ensure that youth players possess sufficient muscular strength capabilities to cope with the increased training and match demands, which can lead to increased thigh musculature strain injury risk (Price et al. 2004). In order to implement appropriate strength training strategies for youth players, practitioners are to utilise relevant methods of assessing thigh musculature strength for identifying potential injury risk and monitoring training progress.

Recent literature has begun to question the ability of isokinetic strength assessments to predict injury risk in soccer (Lee et al. 2017; Van Dyk et al. 2016, 2017). The lack of efficacy in isokinetic profiling could potentially be attributed to methodological limitations in quantifying strength, such as negating the effects of testing velocity and joint angle when determining thigh muscular strength, as identified by the thesis. Although angle-specific measures of isokinetic strength have been assessed in senior soccer players (Cohen et al. 2015; El-Ashker et al 2015; Evangelidis et al. 2015), this has not previously been utilised in elite youth male soccer players. The use of angle and velocity specific assessments of the thigh musculature were identified to be modified by acute bouts of exercise during rehabilitation in a professional male soccer player, thus these measures may also be influenced by prolonged exposure to soccer specific exercise. In turn, angle and velocity specific measures of isokinetic strength may identify whether youth male soccer players possess increased strength discrepancies and imbalances when compared to senior aged players, in accordance with previous epidemiological observations.

The aforementioned isokinetic procedures and metrics may identify a more holistic profile of related factors that could inform the prescription of age specific strength and conditioning in an attempt to reduce injury risk, in particular to youth male soccer players. The current study aims were to assess and compare the strength characteristics of eccKF and conKE musculature of youth and senior soccer players using both traditional (PT, APT, and DCR) and angle-specific isokinetic metrics (AST, FR, AST and DCR_{AST}). It was hypothesised that youth players would possess strength deficits and/or imbalances of the thigh musculature that may be associated with greater injury risk. Highlighting strength deficits should subsequently inform opportunities for training interventions to correct for between group differences.

6.2 Methods

Participants

An a priori power calculation (G*Power 3.0.10) was conducted using pilot study data, with 17 participants being identified for each age group to evaluate the interactions for all dependent variables (for statistical power .0.8; $P \leq 0.05$). Therefore, seventeen senior professional soccer players (age 25.09 ± 3.83 years; height 182.46 ± 3.82cm; mass 83.23 ± 10.01kg) and seventeen elite youth soccer players (age 17.00 ± 0.6 years; height 179.69 ± 4.75cm; mass 70.18 ± 6.33kg) from the same club in the English Soccer League Division Two were recruited. To control for previous injury, all players were free from lower limb injury for > 6 months prior to data collection. In addition to weekly matches, the two groups possessed similar weekly training volumes of ~10hr·week^{-1}. The health screening procedure comprised the completion of a health, physical activity and pre-exercise control questionnaire and the measurement of resting heart rate and blood pressure. Values of >90 beats·min^{-1} and >140 mmHg/90 mmHg respectively were contraindications to exercise. All participants were informed of the associated risks associated with this study before providing written consent. Parent/guardian consent was also obtained for the youth players aged below 18 years. The current study was also approved by a local university ethics committee. All equipment was risk assessed and calibrated in accordance to the manufacturer's guidelines.

Statistical Analysis

To establish whether statistically significant differences existed between the senior and youth playing ages, a repeated measures GLM was performed. The assumptions associated with a repeated GLM were assessed to ensure model adequacy. To assess residual normality for each dependant variable, q-q plots were generated using stacked standardised residuals. Scatterplots of the stacked unstandardised and standardised residuals were also utilised to assess the error of variance associated with the residuals. Mauchly's test of sphericity was also completed for all dependent variables, with a Greenhouse Geisser correction applied if the test was significant. Where significant main effects or interactions were observed, post hoc pairwise comparisons with a Bonferonni correction factor were applied with 95% CI for differences were also reported. Partial eta squared (η^2) values were calculated to estimate effect sizes for all significant main effects and interactions. Partial eta squared was classified as small (0.01 to 0.059), moderate (0.06 to 0.137) and large (>0.138) (Cohen, 1988). All statistical analysis was completed using PASW Statistics Editor 22.0 for windows (SPSS Inc, Chicago, USA). Statistical significance was set at $P \leq 0.05$.

6.3 Results

Peak Torque

No significant four-way interaction between limb, contraction, angular velocity, and age ($P = 0.782$; $\eta^2 = 0.008$) was identified for PT. A significant three-way interaction for limb, contraction, and age (P = 0.047; η^2 = 0.118) was however identified, with the eccKF (Senior 198.9 ± 30.9Nm; Youth = 158.3 ± 30.1Nm; 95%CI: 21.6 to 59.6Nm; P < 0.001) and conKE (Senior = 208.7 ± 23.27Nm; Youth = 173.6 ± 27.4Nm; 95%CI: 15.5 to 46.4Nm; P < 0.001) data recorded for the dominant limb being significantly higher for senior players when compared to the youth players. A similar trend was observed for the eccKF (Senior = 178.8 ± 20.8Nm; Youth = 150.4 ± 25.8Nm; 95%CI: 13.8 to 43.0Nm; P < 0.001) and conKE (Senior = 204.5 ± 30.7Nm; Youth = 168.2 ± 29.8Nm; 95%CI: 21.3 to 59.7Nm; P < 0.001) data recorded for the non-dominant limb. The ICC values calculated for the Senior and Youth conKE PT data recorded at 60°·s^{-1} (Senior: 0.91, Youth: 0.87), 180°·s^{-1} (Senior: 0.87, Youth: 0.89), and 270°·s^{-1} (Senior: 0.83, Youth: 0.84) were almost perfect. Likewise, the ICC values calculated for the Senior and Youth eccKF PT data recorded at 60°·s^{-1} (Senior: 0.88, Youth: 0.84), 180°·s^{-1} (Senior: 0.85, Youth: 0.89), and 270°·s^{-1} (Senior: 0.83, Youth: 0.82) were almost perfect.

Dynamic Control Ratio

For the DCR data (Table 6.1, the GLM did not identify a significant three-way interaction for limb, angular velocity and age (P = 0.508, η^2 = 0.021), nor any two-way interactions for limb and angular velocity (P = 0.294; η^2 = 0.038), limb and age (P = 0.116; η^2 = 0.076) and angular velocity and age (P = 0.115, η^2 = 0.067). There was a significant main effect for limb (P = 0.017; η^2=0.166), with higher values recorded for the dominant limb (0.98 ± 0.19) when compared to the non-dominant limb (0.91 ± 0.16; 95% CI: 0.01 to 0.13). A significant main effect for angular velocity (P < 0.001; η^2 = 0.809) was also identified with higher values recorded at 270°·s^{-1} (1.13 ± 0.22) when compared to both 180°·s^{-1} (0.96 ± 0.15; 95%CI: 0.12 to 0.24) and 60°·s^{-1} (0.75 ± 0.16; 95%CI: 0.32 to 0.45) and significantly higher values recorded at 180°·s^{-1} when compared to 60°·s^{-1} (95%CI: 0.15 to 0.26). The ICC values calculated for the Senior and Youth DCR data recorded at 60°·s^{-1} (Senior: 0.85, Youth: 0.83), 180°·s^{-1} (Senior: 0.83, Youth: 0.80), and 270°·s^{-1} (Senior: 0.79, Youth: 0.77) were substantial to almost perfect.

Angle of Peak Torque

A significant four-way interaction for limb, contraction, angular velocity and age (*P* = 0.048; η^2 = 0.088) was identified for the APT data. Post-hoc pairwise comparisons identified the senior player's dominant limb eccKF PT recorded at 270°·s^{-1} (42 ± 12 º) occurred at significantly increased knee extension angles when compared to youth (57 ± 17 º; 95%CI: -25. to -5 º; *P* = 0.06). The ICC values calculated for the Senior and Youth conKE APT data recorded at 60°·s^{-1} (Senior: 0.73, Youth: 0.68), 180°·s^{-1} (Senior: 0.69, Youth: 0.67), and 270°·s^{-1} (Senior: 0.66, Youth: 0.70) were substantial. Likewise, the ICC values calculated for the Senior and Youth eccKF APT data recorded at 60°·s^{-1} (Senior: 0.74, Youth: 0.70), 180°·s^{-1} (Senior: 0.69, Youth: 0.70), and 270°·s^{-1} (Senior: 0.72, Youth: 0.65) were also substantial.

Functional Range

For the FR data, the GLM did not identify a significant four-way interaction for limb, contraction, angular velocity and age (*P* = 0.854; η^2 = 0.001), nor did it identify significant three-way interactions for limb, contraction and angular velocity (*P* = 0.218; η^2 = 0.047), limb, angular velocity and age (*P* = 0.301; η^2 = 0.128), or limb, contraction and age (*P* = 0.926; η2 < 0.001). As identified in Table 6.1, a significant contraction, angular velocity and age interaction (*P* = 0.006, η^2 = 0.147) was identified, with senior player's eccKF FR being higher than the youth players. The ICC values calculated for the Senior and Youth conKE FR data recorded at 60°·s^{-1} (Senior: 0.83, Youth: 0.78), 180°·s^{-1} (Senior: 0.85, Youth: 0.77), and 270°·s^{-1} (Senior: 0.79, Youth: 0.78) were substantial. Likewise, the ICC values calculated for the Senior and Youth eccKF FR data recorded at 60°·s^{-1} (Senior: 0.84, Youth: 0.81), 180°·s^{-1} (Senior: 0.80, Youth: 0.76), and 270°·s^{-1} (Senior: 0.81, Youth: 0.73) were also substantial to almost perfect.

Table 6.1. The influence of angular velocity on PT and DCR in senior and youth players.

Metric	Angular Velocity (°·s^{-1})	Senior		Youth	
		Dominant	Non-dominant	Dominant	Non-dominant
Hamstrings Torque	60	204.7 ± 38.9	180.2 ± 24.2	154.1 ± 28.6	143.9 ± 26.4
	180	195.3 ± 34.4	178.5 ± 19.9	161.5 ± 29.1	153.0 ± 28.6
	270	195.9 ± 19.5	177.7 ± 18.2	159.5 ± 32.6	154.3 ± 26.4
Quadriceps Torque	60	246.8 ± 26.1	242.3 ± 37.1	215.9 ± 34.4	205.9 ± 35.2
	180	196.9 ± 19.6	206.0 ± 29.4	166.8 ± 21.7	162.6 ± 26.3
	270	170.8 ± 25.4	177.9 ± 25.7	138.3 ± 26.1	136.1 ± 27.8

Angle Specific Torque

As identified in Table 6.2, a significant five-way interaction for angle, angular velocity, limb, age and contraction (P = 0.030, η^2 = 0.078) was identified for the AST data. It was identified the majority of the dominant limb AST data was higher in senior players when compared to youths. However, these differences were less pronounced in the eccKF AST data recorded for the non-dominant limb. Table 5.2 also identifies angle-specific bilateral strength differences, with senior players demonstrating significantly higher dominant eccKF strength across joint angles recorded at 60 and 270°·s^{-1} when compared to the non-dominant side. This response was not however observed for the youth players. The ICC values calculated for Seniors and Youths between 70-40º for conKE AST ranged between 0.91-0.86, 0.92-0.83, and 0.86-0.82 for data recorded at 60°·s^{-1}, 180°·s^{-1} and 270°·s^{-1}, respectively, were almost perfect. Likewise, the ICC values calculated for Seniors and Youths between 70-40º for eccKF AST ranged between 0.90-0.81, 0.89-0.83, and 0.85-0.80 for data recorded at 60°·s^{-1}, 180°·s^{-1} and 270°·s^{-1}, respectively, were almost perfect.

Angle Specific Dynamic Control Ratio

A significant four-way limb, angular velocity, angle and age interaction (P = 0.031; η^2 = 0.069) was identified for the DCR_{AST} data. No significant differences in DCR_{AST} data were identified between age groups in the dominant limb. However, for the data recorded from the non-dominant limb, significantly higher DCR_{AST} data was recorded at 270°·s^{-1} for the youth players when compared to senior players at both 70º (Youth = 1.20 ± 0.34; Senior = 0.99 ± 0.15; 95%CI: 0.02 to 0.39; P = 0.03) and 60º (Youth = 1.13 ± 0.28; Senior = 0.90 ± 0.20; 95%CI: 0.05 to 0.40; P = 0.01) of knee flexion. The ICC values calculated for Seniors and Youths between 70-40º for DCR_{AST} ranged between 0.88-0.82, 0.86-0.79, and 0.83-0.77 for data recorded at 60°·s^{-1}, 180°·s^{-1} and 270°·s^{-1}, respectively, were substantial to almost perfect.

Table 6.2 The influence of angular velocity, angle, and limb on isokinetic torque in senior and youth players. 95% confidence intervals for difference are also presented.

Angle (°)		70		60		50		40	
Group		Senior	Youth	Senior	Youth	Senior	Youth	Senior	Youth
270°·s^{-1}	Dominant eccKF (Nm)	154.3 ± 19.0 *(2.2 to 29.7)	138.3 ± 20.3	164.9 ± 31.2 *(17.7 to 59.4) ~(8.1 to 39.9)	126.3 ± 28.3	180.2 ± 34.4 *(23.2 to 70.0) ~(9.7 to 41.3)	133.5 ± 32.5	192.5 ± 35.6 *(30.9 to 79.4) ~(5.7 to 45.0)	137.3 ± 33.8
	Non-dominant eccKF (Nm)	147.9 ± 12.0	136.8 ± 20.7	140.9 ± 21.0	132.4 ± 27.5	154.7 ± 21.0	135.5 ± 40.5	167.1 ± 23.7 *(3.1 to 50.4)	140.4 ± 41.5
	Dominant conKE (Nm)	155.9 ± 36.9 *(3.1 to 47.2)	130.7 ± 25.0	147.1 ± 21.4 *(2.4 to 30.3)	130.7 ± 18.4	125.5 ± 22.0 *(10.1 to 40.3)	100.4 ± 20.9	111.6 ± 18.5 *(7.7 to 32.0)	91.7 ± 16.2
	Non-dominant conKE (Nm)	152.6 ± 25.6 *(9.0 to 52.9)	121.6 ± 36.2	160.1 ± 25.0 *(25.9 to 56.0)	119.2 ± 17.5	127.6 ± 23.5 *(7.4 to 42.1)	102.8 ± 26.3	121.7 ± 21.2 *(20.5 to 56.2)	83.4 ± 29.1
180°·s^{-1}	Dominant eccKF (Nm)	140.7 ± 28.8 *(7.4 to 40.8)	117.0 ± 16.2	154.6 ± 29.50 *(8.7 to 44.0)	128.3 ± 20.1	169.3 ± 32.6 *(11.7 to 51.2)	137.8 ± 23.3	185.7 ± 34.2 *(18.4 to 63.0)	144.9 ± 29.7
	Non-dominant eccKF (Nm)	132.1 ± 24.4	121.6 ± 27.2	142.2 ± 28.4	135.9 ± 28.9	155.7 ± 29.1	142.2 ± 35.0	170.2 ± 27.2	153.2 ± 36.6
	Dominant conKE (Nm)	173.6 ± 15.3 *(12.1 to 37.1)	149.0 ± 20.2	169.3 ± 30.1 *(8.9 to 42.2)	143.7 ± 15.3	147.6 ± 27.4 *(6.7 to 41.5)	123.4 ± 21.8	127.7 ± 32.4 *(14.6 to 53.4)	93.7 ± 22.2
	Non-dominant conKE (Nm)	183.0 ± 31.4 *(18.7 to 55.4)	146.0 ± 20.0	177.8 ± 28.3 *(8.2 to 47.6)	149.9 ± 28.2	163.1 ± 25.3 *(13.7 to 48.4)	131.8 ± 25.0	136.2 ± 24.6 *(18.2 to 53.6)	100.2 ± 26.0

60°·s^{-1}	Dominant eccKF (Nm)	152.0 ± 27.4 *(19.2 to 54.8) ~(9.1 to 30.0)	115.0 ± 23.5	167.2 ± 30.2 *(21.1 to 62.9) ~(9.4 to 31.0)	125.2 ± 29.6	181.1 ± 34.6 *(19.5 to 63.8) ~(7.7 to 35.0)	139.4 ± 28.5	188.6 ± 39.6 *(21.9 to 70.3)	142.5 ± 28.9
	Non-dominant eccKF (Nm)	132.7 ± 26.6 *(1.2 to 39.3)	112.4 ± 26.9	146.8 ± 29.6 *(2.5 to 43.9)	123.5 ± 29.7	159.9 ± 28.7 *(7.6 to 49.0)	131.5 ± 30.4	172.6 ± 25.7 *(20.7 to 62.7)	130.9 ± 33.8
	Dominant conKE (Nm)	233.2 ± 35.1 *(13.7 to 70.9)	190.9 ± 46.1	202.4 ± 34.0 *(24.2 to 68.9)	155.8 ± 29.9	172.7 ± 27.3 *(23.7 to 59.1)	131.3 ± 23.2	142.8 ± 20.0 *(24.4 to 53.0)	104.2 ± 20.8
	Non-dominant conKE (Nm)	230.7 ± 34.1 *(14.5 to 70.9)	188.0 ± 45.7	204.4 ± 36.6 *(11.8 to 69.7)	163.6 ± 45.8	178.6 ± 38.0 *(19.5 to 71.4)	133.1 ± 36.2	146.4 ± 31.7 *(16.3 to 58.5)	109.0 ± 28.6

(*) demotes a significant difference between playing age, (~) demotes a significant difference between lower limbs

6.4 Discussion

The purpose of this study was to assess and compare the strength characteristics of eccKF and conKE musculature between youth and senior soccer players using both traditional and angle-specific isokinetic metrics. It was identified that there were no statistical differences in eccKF and conKE PT and DCR across the two groups across all angular velocities, suggesting equivalence and potentially identifying training needs incorrectly. There was however significantly higher AST values identified for the senior players compared to youths for eccKF and conKE at all angular velocities throughout the defined angular range in both lower limbs. Furthermore, senior players were also able to elicit a larger FR and APT closer to knee extension at 270°·s^{-1} for the eccKF musculature. Although DCR_{AST} was significantly higher in the youth players compared to seniors at 270°·s^{-1}, these findings were observed at 70 and 60º of knee flexion and may not be meaningful since thigh musculature injuries occur at increased knee extension angles (Chumanov et al. 2012). The present data suggest strength and conditioning coaches should utilise angular velocity and angle-specific measures of isokinetic strength to inform subsequent training interventions. Specific training interventions may then be implemented to increase force production at higher knee angular velocities during increased knee extension where players are most susceptible to muscular strains (Chumanov et al. 2012).These measures are able to inform angular velocity and angle-specific exercise prescription for the development of lower limb musculature strength for the reduction of injury risk and benefit performance, particularly with youth players.

The non-significant differences observed in the current PT and DCR data are not in support of previous findings that identified differences in eccKF and conKE PT data recorded across different soccer playing ages (Gür et al. 1999; Kellis et al. 2001). It should be acknowledged these studies utilised more extreme differences in playing ages (10-25 years) when compared to the current study, suggesting these metrics may only be sensitive to more pronounced physical differences such as, but not limited to, age, adolescent growth, training history, training exposure and injury status (De Ste Croix et al. 2002; Van Der Sluis et al. 2015; Wrigley et al. 2012). As such, alternative isokinetic metrics are advocated to compare thigh musculature strength between players with more comparable characteristics and weekly training loads. The current PT and DCR data is therefore in support of recent research that has questioned the sensitivity of these metrics in identifying players who possess increased risk of injury (LeGall et al. 2006; Renshaw and Goodwin, 2016).

The APT and FR of youth players have not been previously compared to senior players, limiting comparisons to previous studies. For example, the FR metric that was developed has only previously been assessed in professional male soccer players (first study of the thesis). The current data identified that the APT data recorded at 270°·s^{-1} in the senior players occurred at significantly increased knee extension angles when compared to the youth players. The senior players were also able to generate a significantly larger eccKF FR at 270°·s^{-1} in comparison to youth players. When considering the aetiology of thigh muscular strains and knee ligamentous injuries (Boden and Dean, 2000; Chumanov et al. 2012), the observed differences in the APT and FR data suggests the youth players may be at an increased risk of thigh musculature injuries compared to senior players. The first experimental chapter of the thesis identified a player's FR depends on both the angular testing velocity and contraction type. Whilst this was also the case in this present study, eccKF FR in youth players reduced with increased angular velocity; however, this was not identified in senior players. With this in mind, youth players may be at further increased risk of KF injury compared to senior players. As a result, practitioners should identify the APT and force maintenance throughout knee range of motion. These findings reinforce the importance of using increased angular velocities to help determine injury risk (Nedergaard et al. 2014). Therefore, practitioners may need to consider the implications of velocity specific training for improving strength discrepancies at higher angular velocities. Similarly, it has been previously identified that training at higher velocities improves force production in high-speed movements through the use of Olympic lifting and manipulating contraction speed of traditional exercises (Kawamori et al. 2004, 2006). The aforementioned exercises can also be performed at precise knee joint angles to promote further muscular strength increases at specific angles (Barak et al. 2004; Mcmahon et al. 2014) and may also be used in conjunction with specific contraction velocities.

As previously mentioned, the current AST data was significantly higher in senior players when compared to youth players across both limbs and across angular velocities. It must be noted the differences between playing ages were less pronounced when comparisons were made to the non-dominant eccKF data. These findings demonstrate senior players displayed greater limb asymmetry, potentially predisposing the non-dominant limb to an increased risk of KF injury (Croisier et al. 2008). The increased limb asymmetry in senior players may also be linked to frequent single leg movement patterns encountered during soccer specific exercises (Nedergaard et al. 2014), developing a progressively increased limb dominance with playing age. These data suggest that limb asymmetries are developed as a result of prolonged soccer exposure and, as such, these asymmetries can be comparably reduced with a change in practice. The findings of the current study therefore suggest practitioners should consider bilateral asymmetries beyond the assessment of traditional isokinetic metrics and also include AST comparisons in senior and youth soccer players.

Although DCR_{AST} was unable to distinguish between youth and senior players at 60 and 180°·s^{-1}, it was sensitive to age at 270°·s^{-1}, with the youth players eliciting significantly higher DCR_{AST} values in the non-dominant limb at knee flexion angles of 70 and 60°. The observed differences in the DCR_{AST} data can be accounted by higher conKE relative to eccKF values in senior players' non-dominant limb. Furthermore, these findings do not necessarily suggest the observed differences in the DCR_{AST} data may be associated with an increased injury risk, since the differences between playing ages were identified in flexed knee positions, where injury typically does not occur (Chumanov et al. 2002). The present findings are in support of previous research identifying DCR_{AST} differences between different standards of players (Cohen et al. 2015; Evangelidis et al. 2015), but their ability to distinguish between injured and non-injured soccer players and ability to predict injury risk have yielded equivocal findings (Lee et al. 2017; Van Dyk et al. 2016, 2017). Therefore, further prospective studies may wish to analyse these metrics to identify their association with injury risk.

There are also limitations of this study that require identification .Although not directly assessed in this present study, torque was not normalized relative to body mass, where additional differences may also exist. However, normalization of isokinetic strength overcorrects for mass and strongly correlates with torque of the thigh musculatures (Zvijac et al. 2014). Irrespective of the aforementioned limitations, isokinetic dynamometry and muscular strength testing is a common practice in soccer. It is therefore important for sports scientists and fitness coaches alike to identify the limitations of equipment, but as identified in the current study, practitioners should attempt to develop methods to better utilise equipment to further inform practice.

6.5 Conclusion

Isokinetic assessment is often used to quantify thigh musculature strength, with interpretation of the data informing strength training interventions. However, the current study highlights that commonly used metrics such as PT, and the derived DCRs, might lead to mis-interpretation of an athlete's needs. It is therefore recommended that isokinetic evaluation should be performed at specific joint angles, and with specific relevance to performance goals and/or injury risk. Furthermore, isokinetic assessments should be conducted across a range of velocities with greater functional specificity. In the current study, only when angle-specific measures of isokinetic strength were considered across testing velocities were youth players identified as possessing impaired strength when compared to their senior counterparts. As previously identified by the thesis, female soccer players are also suggested to be an increased risk of injury when compared to male soccer players, and further exacerbated in youths. As such there appears a need to consider these additional procedures and metrics to determine thigh musculature strength in female soccer players, relative to playing age.

CHAPTER 7

Isokinetic Strength Differences Between Elite Senior and Youth Female Soccer Players

7.1 Introduction

The thesis identified that the traditional metrics used to determine thigh musculature strength between senior and youth male soccer players were not statistically significant. When the addition of angle-specific measures were included, youth players were identified to possess a significantly reduced strength capacity of the thigh musculature, with potential implications for injury. However, it is yet to be established if senior and youth female soccer player demonstrates similar observations, and requires further research.

Previous epidemiology research has also identified thigh and knee injuries being most prevalent in elite senior and youth female soccer players (Faude et al. 2005; LeGall et al. 2008), with youth players possessing an increased match-play injury incidence (~23 injuries) when compared to their senior counterparts (~18.5 injuries) (LeGall et al. 2008). The higher injury incidence in youth female soccer players has been associated with adolescent growth whereby players undergo a maturational change in stature that is disproportionate to the development of muscular strength (Hewett et al. 2006). Adolescent growth therefore results in an absolute muscular strength discrepancy between youth players and their senior peers indicative of an increased injury risk, impaired physical performance, and a reduced capacity to maintain postural control (De Ste Croix et al. 2002; Hewett et al. 2004). Although it could be suggested that the strength capacity of the two cohorts of players is relative to their maturational status (Manson et al. 2014), the demands of senior match-play and their respected training volumes are far greater than those experienced by adolescent players (Wrigley et al. 2012; Taylor et al. 2017). The observed discrepancies in injury incidence may therefore be associated with ineffective or inappropriate strength and conditioning practices that are currently used with adolescent players in an attempt to better prepare them for the demands of match-play alongside their senior colleagues.

Strength is a primary and modifiable risk factor for thigh musculature strains in soccer (Croisier et al. 2008; Lee et al. 2017) and traumatic knee injuries in adolescent female athletes (Augustsson and Ageberg, 2017). In elite soccer, lower limb strength assessments are often completed using isokinetic dynamometry (Greig, 2008; Fousekis et al. 2011; Lee et al. 2017); however, limited focus has been afforded to elite female soccer players. Previous literature has used isokinetic dynamometry to compare male players of different playing ages (Gür et al. 1999; Kellis et al. 2001; Fousekis et al. 2011). This approach could be used with female players to better prescribe age specific strength and conditioning (Manson et al. 2014), and screen for potential injury risk (Söderman et al. 2002). Profiling of injury risk and prescription of exercise may be further complemented by angle and velocity specific measures of isokinetic strength. As the previous experimental chapter of the thesis identified no significant differences in PT across elite male soccer playing ages, AST was able to determine increases strength deficits in youths. Therefore, the inclusion of angle and velocity specific measures of isokinetic strength assessment may also identify similar observation in youth female soccer players when compared to senior aged players. Whilst these metrics have been previously quantified in male soccer players (Evangelidis et al. 2015), they are currently unexplored in female players, thus allowing better comparisons between groups and the identification of players at increased risk of injury. The current study aims to assess and compare bilateral strength characteristics of the eccKF and conKE musculature of youth and adult female soccer players using the metrics and procedures defined in the thesis.

7.2 Methods

Participants

An a priori power calculation (G*Power 3.0.10) was conducted using pilot study data, with 17 participants being identified for each age group to evaluate the interactions for all dependent variables (for statistical power .0.8; $P \leq 0.05$). Seventeen senior female professional soccer players (age 25.31 ± 4.51 years; height 167.89 ± 7.04cm; mass 63.12 ± 7.79kg) and seventeen female elite youth soccer players (age 16.91 ± 1.16 years; height 165.92 ± 4.42cm; mass 60.07 ± 4.48kg) were therefore recruited. The participants were recruited from the same club with the senior females competing in the Women's Super League 1, the highest standard in female soccer in England. To control for previous injury, all players were free from lower limb injury for >6 months prior to data collection. In addition to weekly matches, player training volume was ~ 10hr·week^{-1} and ~ 5hr·week^{-1} for senior and youth female players, respectively. Prior to each experimental condition, all participants were required to complete a health screening procedure comprising a health, physical activity, and pre-exercise control questionnaire, and the measurement of resting heart rate and blood pressure. Resting heart rate >90 beats·min^{-1} and blood pressure >140 mmHg/90 mmHg, respectively, were contraindications to exercise. All participants were informed of the risks associated with this study before providing written consent. Parent/guardian assent was also obtained for the youth players aged below 18 years. The current study was also approved by a local university ethics committee, at the researcher's host university. Prior to the start of each trial, all equipment was risk assessed and calibrated in accordance to the manufacturer's guidelines.

Statistical Analysis

To establish whether statistically significant differences existed between the senior and youth playing ages, a repeated measures GLM was performed. The assumptions associated with a repeated GLM were assessed to ensure model adequacy. To assess residual normality for each dependant variable, q-q plots were generated using stacked standardised residuals. Scatterplots of the stacked unstandardised and standardised residuals were also utilised to assess the error of variance associated with the residuals. Mauchly's test of sphericity was also completed for all dependent variables, with a Greenhouse Geisser correction applied if the test was significant. Where significant main effects or interactions were observed, post hoc pairwise comparisons with a Bonferonni correction factor were applied with 95% CI for differences were also reported. Partial eta squared (η^2) values were calculated to estimate effect sizes for all significant main effects and interactions. Partial eta squared was classified as small (0.01 to 0.059), moderate (0.06 to 0.137) and large (>0.138) (Cohen, 1988). All statistical analysis was completed using PASW Statistics Editor 22.0 for windows (SPSS Inc, Chicago, USA). Statistical significance was set at $P \leq 0.05$.

7.3 Results

Peak Torque

As summarised in Table 7.1, the GLM identified a significant four-way interaction for age, angular velocity, contraction and limb ($P = 0.016$; $\eta^2 = 0.122$), with significant differences identified between the youth and senior player's in both limbs and across angular velocities. Bilateral differences were also identified for the eccKF data recorded for both groups, with increased discrepancies in the youth players. The ICC values calculated for the Senior and Youth conKE PT data recorded at $60°\cdot s^{-1}$ (Senior:

0.93, Youth: 0.87), 180°·s^{-1} (Senior: 0.91, Youth: 0.89), and 270°·s^{-1} (Senior: 0.87, Youth: 0.81) were almost perfect. Likewise, the ICC values calculated for the Senior and Youth eccKF PT data recorded at 60°·s^{-1} (Senior: 0.86, Youth: 0.87), 180°·s^{-1} (Senior: 0.83, Youth: 0.81), and 270°·s^{-1} (Senior: 0.80, Youth: 0.78) were substantial to almost perfect.

Dynamic Control Ratio

As summarised in Table 672, the GLM did not identify a three-way interaction for age, angular velocity and limb (P = 0.524; η^2 = 0.050). Likewise, no two-way interactions for age and angular velocity (P = 0.679; η^2 = 0.036) or age and limb (P = 0.304; η^2 = 0.071) were identified. There was also no significant main effect for limb (P = 0.101; η^2 = 0.085); however, a significant main effect for angular velocity (P < 0.001; η^2 = 0.454) identified higher values recorded at 270°·s^{-1} (1.30 ± 0.17) when compared to both 180°·s^{-1} (1.16 ± 0.19; 95%CI: 0.27 to 0.73) and 60°·s^{-1} (0.83 ± 0.31; 95%CI: 0.2 to 0.31), and higher values recorded at 180°·s^{-1} when compared to 60°·s^{-1} (95%CI: 0.18 to 0.49). The ICC values calculated for the Senior and Youth DCR data recorded at 60°·s^{-1} (Senior: 0.88, Youth: 0.84), 180°·s^{-1} (Senior: 0.83, Youth: 0.79), and 270°·s^{-1} (Senior: 0.78, Youth: 0.75) were substantial to almost perfect.

Table 7.1
The influence of angular velocity on KF and extensor PT and FR in senior and youth players

Group		Senior PT (Nm)	Youth PT (Nm)	Senior FR (º)	Youth FR (º)
270°·s^{-1}	Dominant eccKF	150.4 ± 24.9 *(3.2 to 34.3)	131.6 ± 19.2 ~(8.5 to 33.1)	28 ± 9	25 ± 10
	Non-dominant eccKF	143.8 ± 29.8 *(15.8 to 50.0)	110.9 ± 17.5	29 ± 10	29 ± 10
	Dominant conKE	112.3 ± 16.4 *(6.5 to 34.7)	91.7 ± 23.4	22 ± 7	18 ± 6
	Non-dominant conKE	115.0 ± 17.0 *(9.9 to 35.4)	92.4 ± 18.6	22 ± 9	19 ± 8
180°·s^{-1}	Dominant eccKF	155.9 ± 20.6 *(7.2 to 37.06)	133.8 ± 22.05 ~(11.4 to 38.6)	24 ± 7	28 ± 10
	Non-dominant eccKF	145.6 ± 31.9 *(18.7 to 54.8)	108.8 ± 17.9	29 ± 12	30 ± 10
	Dominant conKE	131.4 ± 15.6 *(6.4 to 31.0)	112.7 ± 19.4	28 ± 8	25 ± 6
	Non-dominant conKE	131.1 ± 17.8 *(13.5 to 41.1)	103.8 ± 21.6	30 ± 5	29 ± 5
60°·s^{-1}	Dominant eccKF	147.2 ± 27.6 *(8.9 to 40.8) ~(3.5 to 24.9)	122.3 ± 16.7 ~(6 to 27.4)	31 ± 8	34 ± 9
	Non-dominant eccKF	132.9 ± 20.2 *(14.1 to 40.5)	105.6 ± 17.6	33 ± 8	31 ± 9
	Dominant conKE	176.4 ± 24.2 *(6.8 to 41.3)	152.3 ± 25.1	31 ± 8	34 ± 9
	Non-dominant conKE	180.8 ± 28.9 *(17.9 to 55.1)	144.2 ± 24.2	23 ± 6	31 ± 9

(*) demotes a significant difference between playing age, (~) demotes a significant difference between limb.

Table 7.2
The influence of angular velocity on DCR calculated by eccKF: conKE in senior and youth players

Group		Senior	Youth
270°·s^{-1}	Dominant	1.36 ± 0.22	1.55 ± 0.48
	Non-dominant	1.26 ± 0.24	1.23 ± 0.27
180°·s^{-1}	Dominant	1.21 ± 0.14	1.21 ± 0.21
	Non-dominant	1.10 ± 0.19	1.07 ± 0.25
60°·s^{-1}	Dominant	0.84 ± 0.16	0.92 ± 0.31
	Non-dominant	0.74 ± 0.08	0.73 ± 0.14

Angle of Peak Torque

The GLM did not identify a four-way interaction for age, angular velocity, contraction and limb (P = 0.141; η^2 = 0.059). There were also no significant three-way interactions for age, contraction and angular velocity (P = 0.499; η^2 = 0.021), age, limb, and angular velocity (P = 0.060; η^2 = 0.084) and age, limb and contraction (P = 0.854; η^2 = 0.001). The GLM also did not identify a two-way interactions for age and angular velocity (P = 0.178; η2 = 0.053), or age and limb (P = 0.794; η^2 = 0.002). A significant main effect for limb was however identified (P = 0.004; η2 = 0.232) with higher values in the non-dominant limb (56.3 ± 0.2º) when compared to the dominant limb (53.5 ± 0.3º; 95%CI: 1.0 to 4.7º). A significant main effect for angular velocity was also identified (P = 0.001; η2 = 0.206) with data recorded at 270°·s^{-1} (56.9 ± 7.5º) being higher than that recorded at 180°·s^{-1} (52.7 ± 8.6º; 95%CI: 1.6 to 6.8º) and the data recorded at 60°·s^{-1} (55.1 ± 7.7º) being higher than that recorded at 180°·s^{-1} (95%CI: 0.1 to 4.7º). A significant main effect for contraction (P < 0.001; η2 = 0.953) was also identified with the conKE (67.4 to 5.7º) data being higher than eccKF (42.4 ± 10.42º; 95%CI: 23.0 to 27.0º). The ICC values calculated for the Senior and Youth conKE APT data recorded at 60°·s^{-1} (Senior: 0.76, Youth: 0.72), 180°·s^{-1} (Senior: 0.70, Youth: 0.68), and 270°·s^{-1} (Senior: 0.65, Youth: 0.67) were substantial. Likewise, the ICC values calculated for the Senior and Youth eccKF APT data recorded at 60°·s^{-1} (Senior: 0.71, Youth: 0.68), 180°·s^{-1} (Senior: 0.66, Youth: 0.64), and 270°·s^{-1} (Senior: 0.64, Youth: 0.61) were also substantial.

Functional Range

As summarised in Table 7.1, the GLM did not identify a four-way interaction for age, angular velocity, contraction and limb (P = 0.821; η^2 = 0.006). Likewise, no interactions for age, contraction, angular velocity (P = 0.425; η^2 =0.026), age, limb angular velocity (P = 0.333; η^2 = 0.034) or age, limb, contraction (P = 0.147; η^2 = 0.065) were identified. There were also no two-way interactions for age, angular velocity (P = 0.199; η^2 = 0.049), age, contraction (P = 0.255; η^2= 0.040), or for age, limb (P = 0.620; η^2 = 0.008). There was also no significant main effect for limb (P = 0.060; η^2= 0.093); however, a significant main effect for angular velocity (P < 0.001; η2=0.217) was identified, with the data recorded at 270°·s-1 (23.74 ± 7.19º) being significantly lower than that 180°·s-1 (27.64 ± 9.23º) and 60°·s-1 (27.06 ± 9.25º). A significant main effect for contraction was also identified (P < 0.001; η2 = 0.374) with higher values identified in eccKF musculature (28.91 ± 9.87º) when compared to conKE data (23.40 ± 6.86). The ICC values calculated for the Senior and Youth conKE FR data recorded at 60°·s^{-1} (Senior: 0.86, Youth: 0.82), 180°·s^{-1} (Senior: 0.83, Youth: 0.80), and 270°·s^{-1} (Senior: 0.81, Youth: 0.77) were substantial to almost perfect. Likewise, the ICC values calculated for the Senior and Youth eccKF FR data recorded at 60°·s^{-1} (Senior: 0.84, Youth: 0.81), 180°·s^{-1} (Senior: 0.79, Youth: 0.77), and 270°·s^{-1} (Senior: 0.75, Youth: 0.73 were also substantial to almost perfect.

Angle Specific Torque

The GLM identified a significant five-way interaction for age, angular velocity, contraction, limb and angle (P = 0.041; η^2 = 0.081). As summarised in Table 7.3, there were significant differences in the AST recorded across all angular velocities and angles between the senior and youth players. The ICC values calculated for the conKE AST data for all participants between 70 and 40° of knee flexion yielded substantial to almost perfect reliability (0.84-0.95). Likewise, the ICC values calculated for the eccKF AST data for all participants between 70 and 40° of knee flexion yielded substantial to almost perfect reliability (0.78-0.91).

Angle Specific Dynamic Control Ratio

The GLM did not identify a significant four-way interaction between age, angular velocity, limb, and angle (P = 0.053; η^2 = 0.076), nor three-way interactions for age, angular velocity, and angle (P = 0.086; η^2 = 0.092), or limb, angle and age (P = 0.389; η^2 = 0.028). There was however a significant limb, angular velocity and age (P = 0.026; η^2 = 0.122) interaction, with youth players (1.84 ± 0.73) eliciting higher values at 270°·s^{-1} when compared to the senior players (1.46 ± 0.24; 95%CI: 0.20 to 0.73; P = 0.040). The ICC values calculated for the DCR_{AST} data recorded for all participants between 70 and 40° ranged between 0.88-0.79. Likewise, the data recorded across all angular velocities also elicited were substantial to almost perfect reliability (0.83-0.77).

Table 7.3
The influence of angular velocity on knee flexor and extensor AST in senior and youth players. 95% confidence intervals are also presented in parentheses.

Angle (º)		70		60		50		40	
Group		Senior	Youth	Senior	Youth	Senior	Youth	Senior	Youth
270°·s^{-1}	Dominant eccKF (Nm)	127.6 ±12.1 *(6.6 to 22.9)	112.9 ±11.2 *(1.1 to 14.5)	135.5 ± 22.3 *(4.4 to 33.2) ~(0.5 to 20.1)	116.6 ± 18.6 ~(7.3 to 27.5)	145.6 ± 24.0 *(7.5 to 37.1) ~(4.3 to 27.1)	123.4 ± 18.0 ~(8.8 to 31.6)	148.2 ± 25.0 *(7.3 to 38.2) ~(3.4 to 30.4)	125.5 ± 18.8 ~(7.4 to 34.5)
	Non-dominant eccKF (Nm)	121.1 ± 17.0 *(4.3 to 27.8)	105.6 ± 16.6	124.9 ± 22.2 *(12.6 to 38.7)	99.2 ± 14.4	130.0 ± 27.9 *(10.3 to 43.4)	103.2 ± 18.4	131.3 ± 31.2 *(8.4 to 45.2)	104.6 ± 20.4
	Dominant conKE (Nm)	108.0 ± 21.7 *(4.6 to 38.1)	86.7 ± 26.1	103.6 ± 15.0 *(9.7 to 34.3)	81.6 ± 19.9	96.3 ± 15.7 *(10.2 to 36.2)	73.0 ± 21.2	83.4 ± 13.3 *(11.07 to 36.7)	59.5 ± 22.3
	Non-dominant conKE (Nm)	107.1 ± 19.0 *(9.5 to 37.0)	83.9 ± 20.4	101.7 ± 13.4 *(5.5 to 28.1)	84.9 ± 18.5	95.9 ± 15.1 *(9.4 to 30.5)	76.0 ± 15.1	82.5 ± 16.1 *(6 to 30.3)	64.3 ± 18.8
180°·s^{-1}	Dominant eccKF (Nm)	112.8 ± 20.2 *(1.3 to 27.6)	98.4 ± 17.3	127.1 ± 17.5 *(2.5 to 26.7)	112.5 ± 17.1 ~(6.0 to 26.3)	139.5 ± 21.4 *(7.1 to 35.5)	118.2 ± 22.7 ~(6.6 to 28.9)	148.2 ± 21.1 *(6.8 to 35.8)	126.9 ± 20.4 ~(11.5 to 37.4)
	Non-dominant eccKF (Nm)	111.9 ± 21.0 *(10.5 to 36.4)	88.4 ± 15.8	120.6 ± 22.7 *(10.5 to 38.0)	96.3 ± 16.0	125.9 ± 27.7 *(8.8 to 42.1) ~(2.5 to 24.8)	100.4 ± 19.0	128.4 ± 32.8 *(6.5 to 45.3) ~(6.8 to 32.7)	102.5 ± 21.6
	Dominant conKE (Nm)	119.7 ± 16.7 *(5.6 to 29.1)	102.4 ± 17.0	124.4 ± 17.0 *(5.6 to 31.4)	105.9 ± 19.8	115.0 ± 14.9 *(8.9 to 34.0)	93.4 ± 20.4	98.7 ± 17.6 *(9.7 to 36.1)	75.8 ± 20.0

	Non-dominant conKE (Nm)	120.5 ± 15 *(11.4 to 38.4)	95.6 ± 22.8	127.2 ± 16.7 *(18.2 to 43.9)	96.2 ± 19.8	115.2 ± 13.5 *(13. 2to 36.3)	90.4 ± 19.2	99.4 ± 15.9 *(10.4 to 35.4)	76.4 ± 19.7
$60°\cdot s^{-1}$	Dominant eccKF (Nm)	112.5 ± 17.7 *(2.7 to 28.7) ~(3.6 to 18.5)	96.8 ± 19.4 ~(4.8 to 19.8)	125.2 ± 19.0 *(5.0 to 31.3) ~(4.0 to 18.7)	107.0 ± 18.7 ~(7.8 to 22.5)	136.2 ± 20.7 *(10.1 to 37.9) ~(5.6 to 23.1)	112.5 ± 18.2 ~(7.6 to 24.9)	143 ± 23.7 *(15.5 to 50.2) ~(8.6 to 31.5)	110.9 ± 25.7 ~(5.3 to 28.1)
	Non-dominant eccKF (Nm)	101.4 ± 18.6 *(5.3 to 28.5)	84.5 ± 14.3	113.8 ± 18.9 *(10.2 to 33.9)	91.8 ± 14.9	121.9 ± 19.6 *(8.8 to 42.0)	96.3 ± 16.3	123.7 to 19.6 *(14.6 to 44.4)	94.3 to 22.9
	Dominant conKE (Nm)	167.5 ± 32.7 *(2.8 to 44.1)	144.1 ± 26.1	153.1 ± 31.8 *(8.4 to 49.0)	124.4 ± 26.0	129.0 ± 29.7 *(4.4 to 38.8)	107.4 ± 18.2	106.0 ± 23.0 *(2.9 to 30.9)	89.1 ± 16.4
	Non-dominant conKE (Nm)	166.9 ± 23.6 *(10.2 to 43.6)	139.9 ± 24.3	151.4 ± 23.9 *(9.5 o 43.5)	124.9 ± 24.8	128.2 ± 23.9 *(10.9 to 43.0)	101.3 ± 22.0	106.0 ± 22.6 *(8.8 to 38.3)	82.4 ± 19.5

(*) demotes a significant difference between playing age, (~) demotes a significant difference between lower limbs

7.4 Discussion

The purpose of this present study was to assess traditional and angle-specific measures of isokinetic strength of eccKF and conKE musculature between elite senior and youth female soccer players. Across the tested angular velocities, and in both lower limbs, the current data identified that only PT and AST were significantly higher in senior players. The lack of a main effect for playing age across all parameters suggests that practitioners should be mindful of the metrics used to characterise the strength of their players, given the potential implications on training prescription. The influence of movement speed is also of practical value, supporting the need for practitioners to consider strength assessments at high angular velocities.

The between group differences observed for the PT and AST data is in accordance with previous observations (Manson et al. 2014), and these data may be associated with increased injury incidence in youth players (LeGall et al. 2008; Hägglund and Waldén, 2016). The disproportionate changes in skeletal and muscular development (De Ste Croix et al. 2002; Hewett et al. 2004) have implications for increased injury risk (Van Der Sluis et al. 2015). Adolescent growth may also coincide with increased training and match demands as adolescent players begin to train and play alongside their senior peers, and further influence injury risk (Wrigley et al. 2012; Taylor et al. 2017). Thigh musculature strength is a modifiable risk factor for muscular injuries in soccer (Croisier et al. 2008; Lee et al. 2017) and traumatic knee injuries in adolescent female athletes (Augustsson and Ageberg, 2017). The current data highlights the specific needs of youth players in terms of strength development. Peak strength, and the ability to generate force across a range of movement and at high speed, represents elements that can be targeted with an appropriate and periodised strength training intervention (Barak et al. 2004; Kawamori et al. 2004, 2006; Mcmahon et al. 2014. The inability to maintain strength across an increased range of motion, at high speed, could help to explain the observed increase in KF and ACL injuries in youth female players when compared to their senior colleagues (LeGall et al. 2008; Hägglund and Waldén, 2016).

The consideration of angle-specific measurements of isokinetic strength across different testing velocities has been suggested to better consider utility movements commonly performed in soccer and aetiology of injury risk (De Ste Croix et al. 2017; first experimental chapter of the thesis); however, these have only been previously assessed in male soccer players (Cohen et al. 2015; Evangelidis et al. 2015). Although male players were able to elicit higher AST values when compared to females, these aforementioned studies also identified conKE values being highest at ~70° and ~35° for eccKF; thereby displaying higher DCR_{AST} with increased knee extension. The development of strength at particular knee joint angles may consequently be of interest to practitioners for correcting strength discrepancies and reducing injury risk. Angle-specific strength incurs the greatest improvements when training at the corresponding knee joint angle (Barak et al. 2004; Mcmahon et al. 2014). Similarly, training at higher velocities improves force production in high-speed movements (Kawamori et al. 2004; 2006). The manipulation of joint angle and speed is fundamental to the development of strength training interventions, and practitioners may require additional isokinetic metrics to optimise exercise prescription.

Across all angular testing velocities and knee angles, the AST data of the thigh musculature were significantly higher in the senior players when compared to the youth players. The use of AST data is also advocated for the identification of bilateral asymmetries. With potential implications for lower limb injury risk, the current study identified bilateral differences in the eccKF AST data recorded for the youth players, with lower AST data recorded in the player's non-dominant limbs. Bilateral differences have been associated with increased risk of injury in soccer (Croisier et al. 2008), and ACL injuries most commonly occur to the non-dominant limb of youth female soccer players (Hägglund and Waldén, 2016). The reduction of non-dominant eccKF AST may increase the risk of injury given the importance of knee stability (Chmielewski et al. 2005). In order to prevent the development of bilateral asymmetries, youth players may benefit by participating in strength and conditioning practices at a younger age in order to aid the proportionate development of strength (Myer et al. 2013). This may be particularly important in order to ensure that youth players have sufficiently developed strength of both lower limbs prior to them being exposed to training and match-play alongside their more senior peers (Wrigley et al. 2012; Taylor et al. 2017).

The differences relating to PT generation between the groups is most likely a result of increased training exposure (Kellis et al. 2001; Fousekis et al. 2011) and competition demands (Taylor et al. 2017) in the senior players. The PT data is also used to derive metrics such as the DCR, and thus it might be expected that there would be a difference in this metric between the two groups of players. However, this was not the case with the current study and the DCR has limited use in comparing these between players, supporting recent research which questioned the usefulness of ratios in determining injury risk (Dauty et al. 2017; Van Dyk et al. 2017). Further isokinetic strength measures such as APT and FR have been reported in male soccer players in the thesis, but have previously not been considered in female soccer players. The current study did not identify any significant differences between groups of players for APT, or for FR. However, significantly higher DCR_{AST} data was recorded at $270°\cdot s^{-1}$ for the youth players when compared to the senior players. This finding is attributed to the lower conKE strength observed in the youth players, but interpretation must be treated with caution as increased ratios are indicative of reduced injury risk (Croisier et al. 2008; LeGall et al. 2008; Hägglund and Waldén

2016). The DCR and DCR_{AST} data should be interpreted with caution, and in consideration with other metrics, to avoid potential misinterpretation of a player's strength and inappropriately prescribed strength and conditioning practices.

Care should be taken when generalising beyond the specific population and experimental paradigm used. In relating the observations to injury management, it should be noted that the isokinetic phase did not include a full ROM, with data not meeting analysis criterion at full knee extension. When considering the aetiology of lower limb injuries in soccer (Boden and Dean, 2000; Chumanov et al. 2012) the use of increased knee angular velocities could be advocated; however, due to restrictions imposed by the equipment, and the reduced isokinetic phases which are observed at additional angular velocities, it was not possible to collect data at increased knee angular velocities. The current procedures and analytical approaches advance current practice, thus characterising thigh musculature strength with enhanced functional relevance.

7.5 Conclusion

The present study is the first to compare traditional and angle-specific measures of isokinetic strength of eccKF and conKE musculature between elite senior and youth female soccer players. Youth players exhibited significantly less strength, across all speeds, and across a range of knee joint angles. Bilateral strength imbalances were also greater in youth players. The use of AST across a range of testing velocities is advocated to highlight strength deficiencies, and to better inform strength training interventions. Strength ratios can potentially lead to misinterpretation of data, and should be used only in conjunction with the PT values used to derive such ratios. Isokinetic profiling can differentiate between senior and youth players, but should be designed so that the results can directly influence training interventions. As knee ligament injuries are also common in female soccer players and further prevalent in youths, the knee biomechanics exhibited during the assessment of functional movements may also identify differences between playing ages.

SUMMARY OF SECTION A

The series of studies comprised within Section A of the thesis identified that the strength characteristics of the thigh musculature were influenced by knee joint angle and velocity in elite cohorts of soccer players. These observations identified that angle-specific strength values of conKE decreased with higher knee extension angles and velocities. In comparison, angle-specific strength values of eccKF were stable across angular velocities, and increased with greater knee extension angles. As such, these data did not identify a conKE strength dominance relative to injury status, playing age and gender of the soccer player. Although previous literature suggests KF and ACL injury risk is associated with conKE strength dominance, these studies only considered PT values of the thigh musculature at slow testing velocities. As PT is a single point on the torque-angle curve that is commonly determined at low testing velocities consequently limits application to injury, and may influence the lack of association between isokinetic strength assessments and injury risk. Therefore, the defined procedures and metrics in this thesis used to characterise thigh musculature strength may better identify strength deficits and imbalances where lower limb injury typically occurs, when compared to previous methods.

The procedures and metrics defined in this thesis that determined eccKF and conKE strength characteristics were also sensitive to injury status, playing age and gender of the soccer player. Specifically, the traditional PT data and their associated DCR values, including their angle-specific derivatives, were sensitive to injury status, and modifiable through an appropriate training stimulus. The AST strength measures across testing velocities for eccKF and conKE strength were also significantly higher in senior aged soccer players when compared to youths for both genders. However, the traditional PT and DCR metrics were unable to identify significant differences between soccer playing ages for males, although youth female's PT were significantly lower when compared to their senior counterparts. These observations suggest that traditional PT and DCR metrics may only be able to identify significant differences in injured players and those with different weekly training demands. In players with increasingly similar weekly training demands, only AST strength values were able to determine significant differences in soccer playing age. As such, angle-specific measures of thigh musculature strength are advocated to appropriately identify player training needs and differences between soccer playing ages.

The methods determined in Section A of the thesis determines thigh musculature strength at knee joint angles and velocities that better resemble movement patterns associated with injury. Whilst these present procedures are progressive of previous literature, the choice of knee joint angles and velocities used to determine measures of thigh musculature strength were arbitrarily selected in relation to functional movements. Consequently, these present procedures are unable to define strength at precise knee joint angles and velocities exhibited during the completion of functional tasks. Therefore, further considerations are required to determine thigh musculature strength characteristics with enhanced functional relevance with the mechanisms associated with lower limb injury and the demands of soccer. Whilst angle and velocity specific measures of thigh musculature strength are necessary, these metrics may help develop additional screening approaches.

SECTION B

A Kinematic Comparison of the Knee Biomechanics between Senior and Youth Female Soccer Players during Hopping Manoeuvres

Prediction of Thigh Musculature Strength during Hopping Manoeuvres: A Comparison between Female Soccer Playing Age

A Comparison of Predicted Thigh Musculature Strength and Knee Joint Moments in Female Soccer Players

Introduction

Whilst the procedures within Section A of the thesis characterises thigh musculature strength with enhanced functional relevance to movements associated with injury, the knee joint angles and velocities were arbitrarily selected. Nevertheless, knee joint angle and velocity specific measures of thigh musculature strength could be used to inform further development of additional methods for quantifying strength relative to movements associated with injury that are commonly performed in soccer. Thus the aims of Section B of the thesis were to inform further methods of quantifying thigh musculature strength. Since injury risk is relative to age and gender of soccer players, Section B of the thesis will focus on senior and youth female soccer players who are predisposed to an increased injury risk, in particular to traumatic knee injuries. Since previous literature (as identified by the review of literature) has revealed that females exhibit significantly higher knee valgus and knee extensor moments to that of males during the completion of functional tasks, females are suggested to be predisposed to knee ligament injuries due to these increases discrepancies. Previous observations have also identified that ACL injuries are amongst the most concerning injuries in male soccer due to the combined effects of prevalence and severity. Whilst these observations have yet to be identified in females, it could be suggested that with the increase number of ACL injuries in female soccer players, the needs to reduce the risk of injuries in these cohorts are increasingly important. As such, there is also a need to determine the knee biomechanics of senior and youth female soccer players to determine if these cohorts of players exhibit movement patterns that may influence increased ACL injury risk.

As Section A of the thesis identified that strength characteristics of the thigh musculature are influenced by knee joint angle and velocity, these factors should be used to quantify thigh strength. These considerations identified significant differences between senior and youth female soccer players at knee joint angles and velocities that have increased specificity to functional movements, but not specific to those exhibited during the completion of these tasks. Consequently, there may be a need to quantify thigh musculature strength during movements associated with the demands of soccer and mechanisms of lower limb injuries. In order to determine thigh musculature strength during functional tasks associated with lower limb injury, kinematic analysis should identify knee joint angles and velocities exhibited during these movements. In turn, this would indicate whether the thigh musculature are sufficiently developed to manage the demands placed upon the knee joint at specific phases of movement that may increase potential injury risk.

Section B of the thesis comprises three experimental studies. Study 5 is designed to identify the sagittal plane knee joint angles and velocities, relative to female soccer playing age that are exhibited during functional tasks in order to help inform the design of the following study. An additional aim of this study was to compare the sagittal and frontal plane knee joint angles between senior and youth female soccer players during the completion of these functional tasks at various phases of movement. Study 6 is designed to initially identify if knee joint angles and velocities derived from isokinetic dynamometry are statistically significant predictors of thigh musculature strength, relative to female soccer playing age. These statistical approaches would enable the development of predictive equations for quantifying thigh musculature strength during the completion of functional tasks as a function of knee joint angle and velocity. The knee joint angles and velocities exhibited during the completion of functional tasks would consequently determine the strength value elicited by the thigh musculature. Thereafter, using the phases of movement defined in study 5, the predictive equations generated will be used to quantify thigh musculature strength using the knee joint angles and velocities elicited from these tasks. The predicted thigh musculature strength values will be subsequently used to compare between senior and youth female soccer players across the defined phases of movement. Study 7 of the thesis provided additional analyses on the data collected in the previous study. This final study is specifically designed to identify if the moments placed upon the knee joint are disproportionate to the strength capacities of the thigh musculature during functional tasks, and will also be compared between female soccer playing ages across the same defined events. This section comprises of 3 experimental chapters, with the final study split into two parts (study B2 and B3).

CHAPTER 8

A Kinematic Comparison of the Knee Biomechanics between Senior and Youth Female Soccer Players during Hopping Manoeuvres

8.1 Introduction

Strength has consistently been reported as a risk factor for injury in female athletes. As knee joint angle and velocity influence strength characteristics of the eccKF and conKE musculature, there appears a need to determine muscular strength at functionally relevant angles and angular velocities. Knee joint angles and velocities specific to movements associated with injury risk can be determined during biomechanical assessments, and may consequently better inform further methods of quantifying strength. Although strength has been reported as a risk factor for injury in female athletes (Augustsson and Ageberg, 2017), additional modifiable risk factors also exist. Biomechanical factors have been associated with the large number of knee ligament injuries, such as shallow knee flexion accompanied with knee abduction (Hewett et al. 2005; Shimokochi et al. 2009). The aforementioned discrepancies are identified to be further exacerbated during, and following adolescent growth as a result of rapid bone development of the lower limbs and subsequent increase in body mass (Hewett et al. 2004; Hewett et al. 2015). In turn, this creates larger joint torques at the knee, and places an increased demand to maintain postural control (Hewett et al. 2004).

Although risk of knee ligament injury is most commonly determined during biomechanical assessments of vertical drop landing tasks (Hewett et al. 2005; Kernozek et al. 2005; Fox et al. 2017), these movements lack association with directional changes that are suggested to better determine injury risk (Olsen et al. 2004; Pappas et al. 2007; Kristianslund and Krosshaug, 2013). These observations have consequently led to suggestions that sidestep cutting manoeuvres are more appropriate for screening biomechanical markers of knee injury risk, especially when considering the enhanced specificity to injury mechanisms (Krosshaug et al. 2016; Sharir et al. 2016). As such, sidestep cutting manoeuvres are most commonly used to biomechanically assess directional changes (Brown et al. 2014). However, as knee biomechanics are influenced by sidestep and crossover manoeuvres (Besier et al. 2001; Malinzak et al. 2001; Harrison et al. 2008; Ortiz et al. 2011; Potter et al. 2014), these tasks should be considered with cutting angles relevant to the demands of soccer (Bloomfield et al. 2007). Further research have also adapted cutting manoeuvres by using a hopping approach prior to the directional change, and demonstrated significant differences in knee biomechanics between those with and without ACL reconstruction (Rudolph et al. 2000; Ortiz et al. 2011). As hopping manoeuvres exhibit increasingly similar knee angular velocities (~200°·s^{-1}) (Wang, 2011) to those observed during isokinetic strength assessments when compared to running (~3.5m/s) (~500°·s^{-1}) (Ferber et al. 2003), these tasks appear the most appropriate for informing future use of isokinetic dynamometry. These considerations may inform future screening practices by identifying thigh musculature strength at specific knee joint angles and velocities during the completion of functional tasks.

Biomechanical assessments of knee injury risk typically focus analysis during the stance phase of functional movements (Hewett et al. 2005; Landry et al. 2007; Havens and Sigward, 2015), and in particular, following initial ground contact where injury risk has been suggested to further increase (Hewett and Myer, 2011; Norcross et al. 2013). Although functional movements encounter phases of eccentric and concentric muscular actions (De Villarreal et al. 2010; Komi, 2011), biomechanical parameters rarely refer to these loading and propulsive phases of movement. Negative and positive knee angular velocities have been suggested to estimate the eccentric and concentric phases of movement, respectively (Komi, 2011), and could be used to determine the loading and propulsive phases of functional tasks. As the thesis has previously described that strength deficits and imbalances may occur at increased knee angular velocities, these phases of movement could also impair the musculature's ability to maintain postural control. Risk of knee ligament injury and the ability to maintain postural control may also be influenced during deceleration phases of movement (Shimokochi and Shultz, 2008; Boden et al. 2010; Podraza and White, 2010), thus additional discrepancies in sagittal and frontal plane knee joint kinematics could be identified. This would also have implications for the propulsive phases of movement where the change of direction task occurs, and places a demand of the musculature to provide postural control during a period where multiplanar demands are highest (Quatman, Quatman-Yates and Hewett, 2010). The inclusion of loading and propulsive phases may identify the specific time points of biomechanical discrepancies relative to age, limb and manoeuvre. The purposes of this study were twofold: (a) to assess and compare the knee joint angles during sidestep and crossover hopping manoeuvres between senior and youth female soccer players, specific to lower limb, (b) to identify the knee angular velocities exhibited during sidestep and crossover hopping manoeuvres to inform further screening practices.

8.2 Methods

Participants

The participants were recruited from the same club with the senior females competing in the Women's Super League 1, the highest standard in female soccer in England. To control for previous injury, all players were free from lower limb injury for >6 months prior to data collection. In addition to weekly matches, player training volume was ~10hr·week^{-1} and ~ 5hr·week^{-1} for senior and youth female players, respectively. Prior to each experimental condition, all participants were required to complete a health screening procedure comprising a health, physical activity, and pre-exercise control questionnaire, and the measurement of resting heart rate and blood pressure. Resting heart rate >90 beats·min-1 and blood pressure >140 mmHg/90 mmHg, respectively, were contraindications to exercise. All participants were informed of the risks associated with this study before providing written consent. Parent/guardian assent was also obtained for the youth players aged below 18 years. The current study was also approved by a local university ethics committee, at the researcher's host university. Prior to the start of each trial, all equipment was risk assessed and calibrated in accordance to the manufacturer's guidelines.

Statistical Analysis

To establish whether statistically significant differences existed between the senior and youth playing ages, a repeated measures GLM was performed. The assumptions associated with a repeated measures GLM were assessed to ensure model adequacy. To assess residual normality for each dependant variable, q-q plots were generated using stacked standardised residuals. Scatterplots of the stacked unstandardised and standardised residuals were also utilised to assess the error of variance associated with the residuals. Mauchly's test of sphericity was also completed for all dependent variables, with a Greenhouse Geisser correction applied if the test was significant. Where significant main effects or interactions were observed, post hoc pairwise comparisons with a Bonferonni correction factor were applied with 95% CI for differences were also reported. Partial eta squared (η^2) values were calculated to estimate effect sizes for all significant main effects and interactions. Partial eta squared was classified as small (0.01 to 0.059), moderate (0.06 to 0.137) and large (>0.138) (Cohen, 1988). All statistical analysis was completed using PASW Statistics Editor 22.0 for windows (SPSS Inc, Chicago, USA). Statistical significance was set at $P \leq 0.05$.

8.3 Results

Peak Knee Flexion Angle

For all dependent variables associated with the current study, ICC's were calculated between 0.73 and 0.85. As identified in Figure 8.1, the GLM identified a significant three-way interaction for age, limb, and manoeuvre (*P* = 0.038; η^2 = 0.128). Significantly higher knee flexion angles were identified in the sidestep trial for the youth female's dominant limb (53.89 ± 6.94º) when compared to the senior players (47.75 ± 5.56º; 95% CI: 1.79 to 10.54º; *P* = 0.030). The youth females also demonstrated significantly higher peak knee flexion angles for the non-dominant limb (49.65 ± 5.40º) during sidestep trials when compared to senior females (45.65 ± 3.19º; 95% CI: 0.89 to 7.09°; *P* = 0.030).

Initial Contact

The GLM identified no significant interactions for age, limb, and manoeuvre (*P* = 0.145; η^2 = 0.065), age and manoeuvre (*P* = 0.501; η^2 = 0.014), or age and limb (*P* = 0.657; η^2 = 0.006). There was also no significant main effect for limb (*P* = 0.908; η^2 < 0.001); however, there was a significant main effect for manoeuvre (*P* = 0.042; η^2 = 0.123), with higher knee flexion angles in sidestep manoeuvre (47.36 ± 6.82°) when compared to crossover trial (41.90 ± 16.28°; 95% CI: 45.25 to 49.48°).

Loading Phase

The GLM identified no significant interactions for age, limb, and manoeuvre (*P* = 0.335; η^2 = 0.029), nor age and manoeuvre (*P* = 0.692; η^2 = 0.005). However, a significant two-way interaction for age and limb (*P* = 0.044; η^2 = 0.120) was identified, with youth females demonstrating significantly higher knee flexion angles for the dominant limb (26.86 ± 6.42°) when compared to senior females (20.99 ± 7.66°; 95% CI: 1.67 to 10.42°; P = 0.008).

Propulsive Phase

The GLM identified no significant interactions for age, limb, and manoeuvre (P = 0.073; $\eta^2 = 0.097$), age and manoeuvre (P = 0.972; $\eta^2 < 0.001$), nor age and limb (P = 0.650; $\eta^2 = 0.007$). A significant main effect for limb (P = 0.002; $\eta^2 = 0.271$) was however identified, with higher knee flexion angles in the non-dominant limb (30.64 ± 10.53°) when compared to the dominant limb (27.46 ± 9.48°; 95% CI: 1.30 to 5.05°). A significant main effect for manoeuvre (P = 0.047; $\eta^2 = 0.117$) was also identified, with higher knee flexion angles recorded in the sidestep trial (30.79 ± 7.93°) when compared to crossover trial (27.32 ± 12.08°; 95% CI: 0.42 to 6.88°).

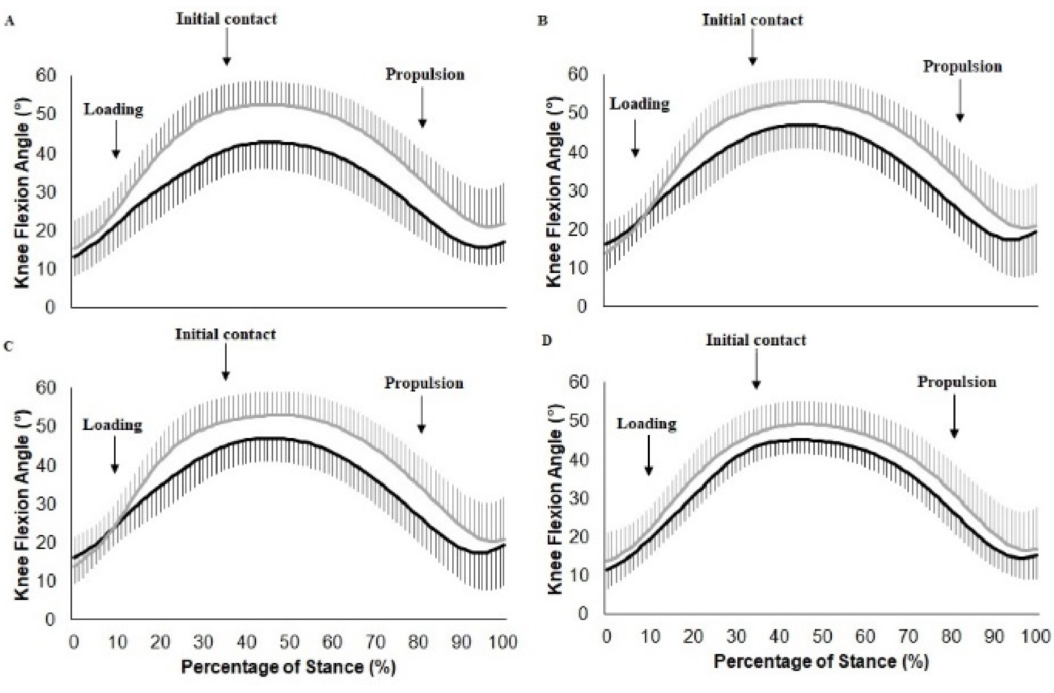

Figure 8.1 illustrates knee flexion angle during the stance phase of hopping manoeuvres for senior (black) and youth (grey) players. A: dominant sidestep; B: non-dominant sidestep; C: dominant crossover; D: non-dominant crossover.

Peak Knee Abduction Angle

As identified by Figure 8.2, the GLM identified no significant interactions for age, limb, and manoeuvre (P = 0.906; $\eta^2 < 0.001$), age and manoeuvre (P = 0.370; $\eta^2 = 0.025$), nor age and limb (P = 0.241; $\eta^2 = 0.043$). A significant main effect for limb (P = 0.003; $\eta^2 = 0.244$) was however identified, with higher peak knee abduction angles in the dominant limb (-3.66° ± 3.26°) when compared to the non-dominant limb (-1.98 ± 2.33°; 95% CI: -2.73 to -6.10°). A significant main effect for the manoeuvre ($P < 0.001$; $\eta^2 = 0.646$) was also identified, with higher peak knee abduction angles recorded during the sidestep trial (-3.70 ± 2.81°) when compared to crossover trial (-1.94 ± 2.77°; 95% CI: -1.29 to -2.22°).

Initial Contact

The GLM identified no significant interactions for age, limb, and manoeuvre (P = 0.947; $\eta^2 < 0.001$), age and manoeuvre (P = 0192; $\eta^2 = 0.053$), nor age and limb (P = 0.344; $\eta^2 = 0.028$). A significant main effect for limb ($P < 0.001$; $\eta^2 = 0.440$) was however identified, with higher knee abduction angles recorded for the dominant limb (-3.02 ± 4.04°) when compared to the non-dominant limb (-0.41° ± 4.23°; 95% CI: -0.92 to -1.76). A significant main effect for manoeuvre (P = 0.047; $\eta^2 = 0.118$) was also identified, with higher knee abduction angles in sidestep trials (-0.87 ± 4.11°) when compared to crossover trials (1.74 ± 4.17°; 95% CI: -0.12 to -1.74°).

Loading Phase

The GLM identified no significant interactions for age, limb, and manoeuvre (P = 0.510; $\eta^2 = 0.014$) and for age and limb (P = 0.279; $\eta^2 = 0.037$). However, a significant two-way interaction for age and manoeuvre (P = 0.025; $\eta^2 = 0.148$) was identified, with senior females eliciting higher knee abduction angles (-0.88 ± 2.78°) during the sidestep manoeuvre when compared to youth females (1.04 ± 3.12°; 95% CI: -0.56 to -1.82°; *P* = 0.048).

Propulsive Phase

No significant interactions for age, limb, and manoeuvre (*P* = 0.307; $\eta^2 = 0.033$), age and manoeuvre (*P* = 0.295; $\eta^2 = 0.034$), nor age and limb (*P* = 0.122; $\eta^2 = 0.073$) were identified. A significant main effect for limb (*P* = 0.001; $\eta^2 = 0.310$) identified higher knee abduction angles in the dominant limb (-1.03 ± 3.45°) when compared to the non-dominant limb (1.08 ± 3.22°; 95% CI: 0.95 to 3.16°). A significant main effect for manoeuvre (*P* < 0.001; $\eta^2 = 0.342$) also identified higher knee abduction angles in sidestep trials (-0.67 ± 3.44°) when compared to crossover trials (0.65 ± 3.12°; 95% CI: -0.39 to -1.76°).

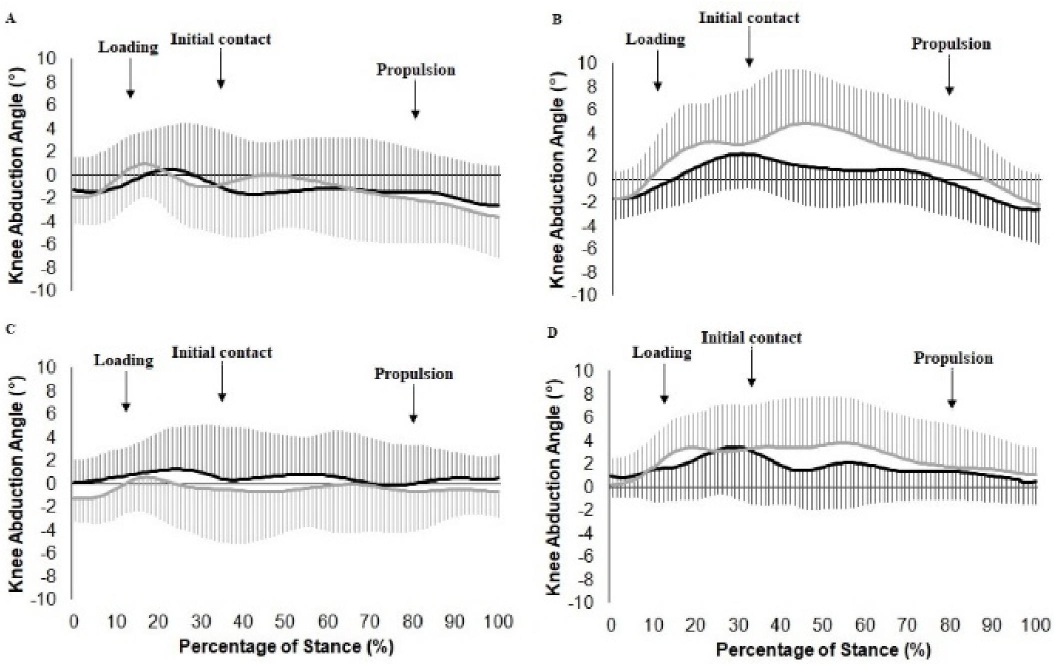

Figure 8.2 illustrates knee abduction angles during the stance phase of hopping manoeuvres for senior (black) and youth (grey) players. A: dominant sidestep; B: non-dominant sidestep; C: dominant crossover; D: non-dominant crossover.

Knee Angular Velocity

Initial Contact

As identified by Figure 8.3, no significant interactions for age, limb and manoeuvre (P = 0.131; η^2 = 0.070), nor two-way interaction for age and manoeuvre (P = 0.265; η^2 = 0.039) were identified. However, a significant two-way interaction for age and limb (P = 0.003; η^2 = 0.239) was identified. Post-hoc analysis revealed senior females non-dominant limb's knee angular velocity was significantly higher (-179.75 ± 104.93°·s^{-1}) when compared to youth females (-108.25 ± 70.16°·s^{-1}; 95%CI: -16.39 to 126.06°·s^{-1}; P = 0.013).

Loading Phase

No significant interactions for age, limb and manoeuvre (P = 0.196; η^2 = 0.052), nor two-way interactions for age and manoeuvre (P = 0.824; η^2 = 0.002), age and limb (P = 0.918; η^2 < 0.001) were identified. There were also no significant main effects for limb (P = 0.693; η^2 = 0.005) and manoeuvre (P = 0.305; η^2 = 0.033).

Propulsive Phase

No significant interactions for age, limb and manoeuvre (P = 0.144; η^2 = 0.065), nor two-way interactions for age and manoeuvre (P = 0.055; η^2 = 0.110), age and limb (P = 0.219; η^2 = 0.047) were identified. There were also no significant main effects for limb (P = 0.439; η^2 = 0.019) and manoeuvre (P = 0.210; η^2 = 0.049).

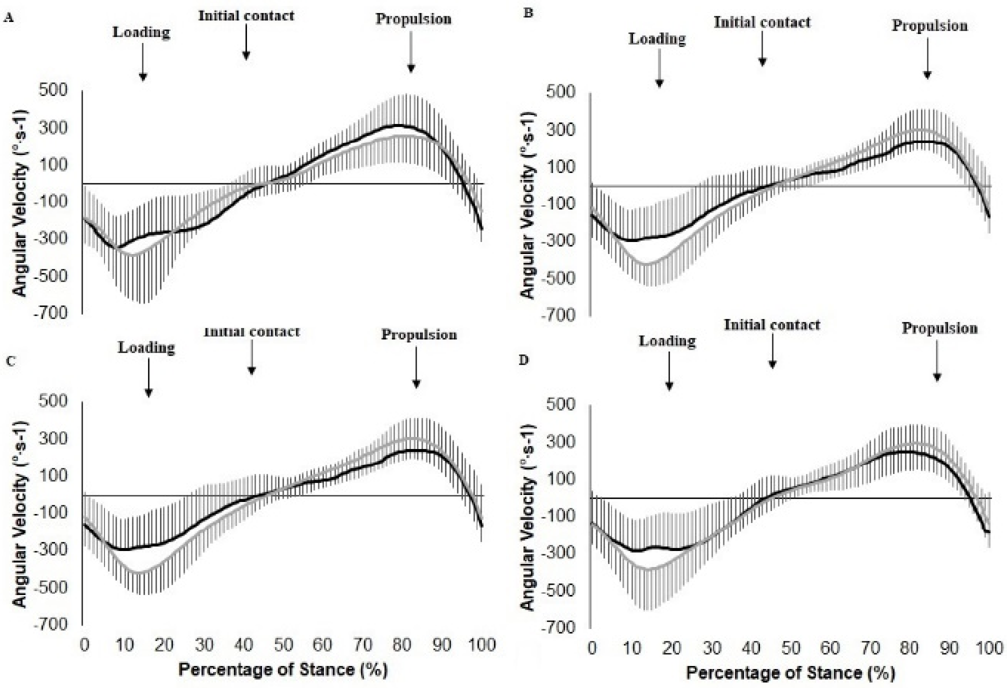

Figure 8.3 illustrates knee angular velocities during the stance phase of hopping manoeuvres for senior (black) and youth (grey) players. A: dominant sidestep; B: non-dominant sidestep; C: dominant crossover; D: non-dominant crossover.

8.4 Discussion

The present study compared the sagittal and frontal plane knee kinematics between senior and youth female soccer players during hopping manoeuvres, relative to lower limb. The hopping manoeuvres were also used to identify the knee angular velocities exhibited during these tasks to inform further screening practices. The current data identified that youth female soccer players exhibited significantly higher peak knee flexion angles in the dominant and non-dominant limbs during sidestep manoeuvres when compared to their senior counterparts. During the loading phase of hopping manoeuvres, and irrespective of cutting manoeuvre, the youth female soccer players also demonstrated significantly higher knee flexion angles in their dominant limb when compared to the senior participants. It was also identified during the loading phase of sidestep hopping manoeuvres that senior females demonstrated significantly higher knee abduction angles when compared to the youth participants. However, previous epidemiological findings identified that youth female soccer players are predisposed to an increased risk of knee ligament injury when compared to senior aged players (Renstrom et al. 2008; Hägglund and Waldén, 2015). These aforementioned observations were postulated to increased discrepancies in sagittal and frontal plane knee biomechanics in youth females (Hewett et al. 2004, 2015). This study also identified that the knee angular velocities exhibited during hopping manoeuvres are similar to those observed during isokinetic dynamometry, and may be used to inform future considerations in assessing thigh musculature strength.

Since this is the first study to compare sagittal and frontal plane knee biomechanics during hopping manoeuvres across female soccer playing ages, comparisons to previous studies are not possible. The present study identified that senior females demonstrated significantly higher knee abduction angles during the loading phase of sidestep hopping manoeuvres when compared to youths. Despite these significant differences, the mean knee abduction angles during the loading phase of sidestep hopping manoeuvres were -0.88° and 1.04° for senior and youth females, respectively. The knee abduction angles identified in the present study were however lower than values previously reported in injured participants during vertical drop landings (~9º) (Hewett et al. 2005). The different knee abduction angles exhibited between the present study and Hewett et al. (2005) would likely be influenced by the different movement tasks and participants used in the respective studies. Moreover, the cohorts of players used in this present study were previously exposed to neuromuscular training, thereby correcting discrepancies in sagittal and frontal plane knee biomechanics (Sugimotio et al. 2012, 2016) and reducing risk of knee ligament injury (Mandelbaum et al. 2005; Gilchrist et al. 2008). T

Irrespective of playing age, literature typically identifies a higher knee ligament injury incidence in the non-dominant limb when compared to the dominant side of female soccer players (Brophy et al. 2010; Waldén et al. 2016). The present study identified significantly higher peak knee abduction angles for the dominant limb when compared to the non-dominant side, irrespective of playing age and cutting manoeuvre. No significant differences were identified between lower limbs for knee abduction angles following initial ground contact where risk of knee ligament injuries is increased (Hewett and Myer, 2011; Norcross et al. 2013). Similar findings for knee abduction angles also identified no significant differences between lower limbs at the loading and propulsive phases of hopping manoeuvres. Although not assessed in the present study, these data appear to suggest that the non-dominant lower limb is not predisposed to an increased risk of knee ligament injury. Nevertheless, these data advocate determining sagittal and frontal plane knee kinematics across a variety of events where the requirements to maintain postural control are highest in order to better identify potential injury risk (Quatman, Quatman-Yates and Hewett, 2010; Hewett and Myer, 2011; Benche et al. 2012; Norcross et al. 2013).

Previous studies that compared between sidestep and crossover cutting manoeuvres (Besier et al. 2001; Malinzak et al. 2001; Potter et al. 2014) identified sagittal and frontal plane biomechanics are influenced by these different directional changes. In accordance with previous observations (Besier et al. 2001; Potter et al. 2014), the present study identified significantly higher knee flexion and abduction angles for sidestep manoeuvres when compared to crossover tasks. The observed differences between these two cutting tasks are likely accounted by the different demands of these directional changes. Specifically, sidestep cuts require the planted lower limb to accelerate opposite to the intended directional change (Cochrane et al. 2001). In contrast, crossover tasks require the planted lower limb to accelerate in the same direction of the intended directional change (Cochrane et al. 2001). These observations have consequently led to suggestions that sidestep cutting tasks may places athletes at greater injury risk to that of crossover manoeuvres. Nevertheless, the evidence to suggest that injury risk is highest during sidestep tasks when compared to crossover movements is limited. As such, biomechanical assessments of change of direction tasks should still utilise sidestep and crossover movements in order to appropriately determine biomechanical metrics of the knee joint associated with injury risk.

The present study also identified that the hopping manoeuvres exhibited angular velocities similar to those observed during isokinetic strength assessments of the thigh musculature, and supported by previous observations (Wang, 2011). Although hopping manoeuvres are suggested to be multiplanar demanding tasks (Rudolph et al. 2000; Ortiz et al. 2011), these movements elicited largely neutral knee joint angles in the frontal plane, thus appears an appropriate task to inform strength assessments conducted in the sagittal plane. Although recent literature (Cohen at al. 2015; El-Ashker et al. 2015; Evangelidis et al. 2015; De Ste Croix et al. 2017) and Section A of the thesis suggests that knee joint angles and velocities should be considered when characterising muscular strength, these arbitrary metrics are unable to determine thigh musculature strength at precise angular velocities and angles exhibited during functional tasks. As such, the knee joint angles and velocities exhibited during hopping manoeuvres may be an appropriate task to determine thigh musculature strength in movements associated with injury, and enable subsequent comparison between female soccer playing age.

As it has been suggested that ACL injury risk is highest during and following 0.1 seconds following ground contact of functional tasks, the sampling frequency of 120Hz used in this study provides only 5 frames of footage to analyse during this period. As such, the camera sampling frequency used in this study may be a limitation, thus further research using higher sampling frequencies may be required in these populations to more appropriately identify injury risk. In light of this, the hopping tasks utilised does not exhibit the ballistic knee joint angular velocities and accelerations to that of cutting manoeuvres, and may be appropriate for determining group differences in knee joint biomechanics. In further support, previous studies that have also utilised hopping tasks have identified biomechanical differences of the knee joint in those who possess varying levels of injury risk (Orishimo et al. 2010; Ortiz et al. 2011), but may not be appropriate for identifying injury risk when ground contact time is limited.

8.5 Conclusion

The present study identified significant differences in sagittal and frontal plane knee kinematics between senior and youth female soccer players during sidestep and crossover hopping manoeuvres. Although not directly assessed in this study, these differences are not indicative of an increased injury risk in either cohorts of soccer players. The sagittal and frontal plane knee kinematics were also influenced by cutting manoeuvre, where larger knee abduction angles were identified during sidestep cutting manoeuvres. These data therefore have implications for choice of biomechanical screening tests. In addition, the specific events during hopping manoeuvres should be considered to appropriately determine knee biomechanics during periods that may have potential implications for knee ligament injury risk screening. Moreover, the knee angular velocities exhibited during hopping manoeuvres were similar to isokinetic strength assessments, and may inform future screening methods. For instance, the thesis previously identified significant strength differences between senior and youth female soccer players, thus these discrepancies may also be observed during functional tasks associated with injury. As knee joint angle and velocity highly influence muscular strength, as identified by

Section A of the thesis, these parameters may be used to identify thigh musculature strength during the completion of hopping manoeuvres.

CHAPTER 9

Prediction of Thigh Musculature Strength during Hopping Manoeuvres: A Comparison between Female Soccer Playing Age

9.1 Introduction

The previous experimental chapter identified limited differences in sagittal and frontal knee kinematics between female soccer playing ages during sidestep and crossover hopping manoeuvres. Nevertheless, youth female soccer players were identified to possess a reduced strength capacity of the thigh musculature at a variety of knee joint angles and velocities in section A. However, biomechanical assessments of functional movements may better inform isokinetic dynamometry in order to use these measurement tools with enhanced synchrony, and identify strength differences between female soccer playing ages at specific phases of hopping manoeuvres. The first part of this present study has therefore been designed to predict thigh musculature strength based on knee joint angles and velocities exhibited during hopping tasks between playing age, limb and manoeuvre in female soccer players.

As previously discussed throughout the thesis, muscular strength is a modifiable risk factor for thigh musculature and knee ligament injuries (Askling et al. 2003; Arnason et al. 2007; Croisier et al. 2008; LeGall et al. 2008; Hartmut et al. 2010; Augustsson and Ageberg, 2017). The thesis has consistently identified that practices associated with isokinetic strength assessments do not commonly determine strength values at specific joint angles and velocities. Although knee joint angle and velocity have clear influences on force production (Cohen at al. 2015; El-Ashker et al. 2015; Evangelidis et al. 2015; De Ste Croix et al. 2017), no study has ascertained whether these metrics are significant predictors of thigh musculature strength. Whilst previous studies have identified that anthropometric data are significant predictors of thigh musculature PT (Gross and McGrain, 1989; Kellis et al. 2000), the ability of knee joint angles and velocities to predict thigh musculature strength has yet to be determined. In turn, knee joint angles and velocities exhibited during functional tasks may be used to predict thigh musculature strength during movements associated with lower limb injury

(Boden and Dean, 2000; Olsen et al. 2004; Chumanov et al. 2012; Higashihara et al. 2015).

Relative to playing age of the female soccer player, knee joint angles and velocities exhibited during hopping tasks appear appropriate to determine KF and KE strength during specific phases of movement. In support, the previous experimental chapter identified mean knee flexion angles and velocities exhibited during hopping tasks of 15 to 55° and -400 to 300°$\cdot s^{-1}$, respectively. As such, knee joint angles and velocities may be able to predict thigh musculature strength during hopping tasks as these metrics are alike to those observed during isokinetic dynamometry. Moreover, these considerations may identify significant differences in predicted thigh musculature strength between senior and youth female soccer players. As youth female soccer players were identified to possess significantly lower thigh musculature strength values when compared to senior aged players (Section A of the thesis), these discrepancies may also be identified during functional tasks associated with lower limb injuries (Boden and Dean, 2000; Olsen et al. 2004; Chumanov et al. 2012; Higashihara et al. 2015). In turn, these screening methods may better identify strength discrepancies that may be associated with a higher number of ACL injuries in female soccer player's non-dominant limb (Brophy et al. 2010; Hägglund and Waldén, 2016) and for youth players who are predisposed to an increase injury risk (LeGall et al. 2008; Renstrom et al. 2008; Hartmut et al. 2010; Waldén et al. 2016).

The aims of the first part of this study were threefold: (a) to identify if eccKF and conKE could be predicted during the completion of sidestep and crossover hopping manoeuvres, (b) to identify if predicted eccKF and conKE would identify significant differences between female soccer players and lower limb, (c) to compare predicted eccKF and conKE between sidestep and crossover hopping manoeuvres relative to playing age and lower limb.

9.2 Methods

Participants

Participants identified in the previous experimental chapter were selected for this present study.

Testing Procedures

The testing procedures comprised the completion of the procedures previously described in the general methods section.

Data Analysis

The isokinetic strength data was initially analysed in accordance with the procedures previously described across a range of knee joint angles and velocities in senior and youth female soccer players. In turn, this determined bilateral isokinetic strength data of the eccKF and conKE at 60, 180 and 270°·s^{-1} between an angular range of 70-40º of knee flexion. These data were subsequently used within the multiple linear regressions to ascertain if knee joint angles and velocities derived from isokinetic strength assessments were significant predictors of thigh musculature strength. If the percentage of variance for knee joint angles and velocities were sufficient, this model would be used to predict thigh musculature strength during hopping manoeuvres. The knee joint angles and velocities exhibited during the completion of hopping manoeuvres at specific phases of movement would subsequently be used to predict thigh musculature strength. The knee joint angles and velocities exhibited during hopping tasks were also analysed in accordance with the described in the previous study.

Statistical Analysis

For the development of the prediction algorithms, multiple linear regressions were used to predict eccKF and conKE strength values, relative to female soccer playing age, at specific knee joint angles and velocities exhibited during particular phases of hopping manoeuvres. Multiple linear regressions were selected on the basis that increased knee joint extension angles coincide with higher and lower eccKF and conKE strength values, respectively. As conKE muscular strength values were also identified to linearly reduce with increased testing velocity in Section A of the thesis, angular velocity was included into the multiple linear regressions. Knee joint angles and angular velocities derived from isokinetic strength assessments therefore served as the independent variables to ascertain whether these parameters could suitably account for the variation in muscular strength. Subsequently, these parameters were used to predict muscular strength during hopping tasks, using the unstandardised coefficients calculated for the constants, knee joint angles and velocities derived from the multiple linear regressions. Predicted strength of eccKF and conKE across all defined events were then compared to ascertain the effects of age, limb, and manoeuvre. All the assumptions associated with multiple linear regression were achieved during the development of the prediction algorithms. Pearson's correlation identified a linear relationship between the independent and dependent variables with addition to visual inspections of scatterplots confirming linearity. Homoscedasticity was identified by visual inspections of plots of standardised residuals versus standardized predicted values, where the residuals achieved normality.

Thereafter, to establish whether statistically significant differences existed between the senior and youth playing ages, the data was analysed using a repeated measures GLM. The assumptions associated with a repeated measures GLM were assessed to ensure model adequacy. To assess residual normality for each dependant variable, q-q plots were generated using stacked standardised residuals. Scatterplots of the stacked unstandardised and standardised residuals were also utilised to assess the error of variance associated with the residuals. Mauchly's test of sphericity was also completed for all dependent variables, with a Greenhouse Geisser correction applied if the test was significant. Where significant main effects or interactions were observed, post hoc pairwise comparisons with a Bonferonni correction factor were applied with 95% CI for differences were also reported. Partial eta squared (η^2) values were calculated to estimate effect sizes for all significant main effects and interactions. Partial eta squared was classified as small (0.01 to 0.059), moderate (0.06 to 0.137) and large (>0.138) (Cohen, 1988). All statistical analysis was completed using PASW Statistics Editor 22.0 for windows (SPSS Inc, Chicago, USA). Statistical significance was set at $P \leq 0.05$.

9.3 Results

Multiple Linear Regressions

The algorithms generated by the multiple linear regressions for the senior female (eccKF = 153.42 – [-0.05*angular velocity]-[-0.70*angle]) (conKE = 80.65 – [-1.90*angular velocity]-[1.18*angle]) and youth female (eccKF = 126.25 – [-0.06*angular velocity]-[-0.50*angle]) (conKE = 80.65 – [-1.80*angular velocity]-[1.23*angle]) soccer players were significant predictors of eccKF and conKE strength during isokinetic dynamometry ($R^2 \geq 0.88$-0.93; $P \leq 0.001$), as identified in Table 9.1. This enabled the prediction of eccKF and conKE strength during the completion of sidestep and crossover hopping manoeuvres relative to female soccer playing age. The unstandardised coefficients were subsequently used to predict muscular strength with the knee joint angles and velocities exhibited during hopping manoeuvres. The prediction equations were:

$$\text{Predicted muscular strength} = \beta\ \text{Constant} - (\beta\ \text{angular velocity} \times \text{angular velocity}) - (\beta\ \text{angle} \times \text{angle}).$$

Table 9.1
Multiple Regressions Coefficients

	Senior Female	**Youth Female**
EccKF		
R^2 and *P* Value	$R^2 = 0.93$; $P < 0.001$	$R^2 = 0.88$; $P < 0.001$
β Constant	153.42 ± 4.47	126.25 ± 5.21
β Angular Velocity	0.05 ± 0.01	0.06 ± 0.1
β Angle	-0.70 ± 0.07	-0.50 ± 0.09
ConKE		
R^2 and *P* Value	$R^2 = 0.89$; $P < 0.001$	$R^2 = 0.89$; $P < 0.001$
β Constant	80.65 ± 13.30	60.11 ± 12.87
β Angular Velocity	-1.90 ± 0.02	-1.80 ± 0.03
β Angle	1.18 ± 0.22	1.23 ± 0.21

Table 9.1 demonstrates that knee joint angle and velocity are statistically significant predictors for eccKF and conKE for senior and youth female soccer players. The unstandardised coefficients (β) are presented with standard error (±).

Predicted Peak Strength

For eccKF, the GLM identified no significant interactions for age, limb and manoeuvre ($P = 0.531$; $\eta^2 = 0.012$), age and manoeuvre ($P = 0.069$; $\eta^2 = 0.099$), nor age and limb ($P = 0.911$; $\eta^2 < 0.001$), as identified by Table 9.2. There were also no significant main effects for manoeuvre of cutting manoeuvres ($P = 0.504$; $\eta^2 = 0.012$) and limb ($P = 0.222$; $\eta^2 = 0.004$).

Predicted Strength at Initial Contact

The GLM identified a significant interaction for age, limb and manoeuvre ($P < 0.001$; $\eta^2 = 0.439$) for eccKF between seniors and youths (Table 9.2). Post-hoc analysis revealed that the senior female's eccKF dominant limb values were significantly higher when compared to youths during sidestep manoeuvres. Additionally, the senior females' eccKF values were significantly higher for dominant and non-dominant limbs during crossover manoeuvres when compared to youths.

Table 8.2 Predicted Isokinetic Torques During Sidestep and Crossover Manoeuvres. 95% CI for Differences are Reported for all Significant Differences.

	Senior		**Youth**		**Senior**		**Youth**	
Event	Dominant	Non-dominant	Dominant	Non-dominant	Dominant	Non-dominant	**Dominant**	**Non-dominant**
	Sidestep Manoeuvre				Crossover Manoeuvre			
Peak Value								
eccKF (Nm)	159.1 ± 11.1	158.4 ± 11.5	139.6 ± 8.8	137.9 ± 14.4	158.2 ± 9.7	154.91 ± 9.3	140.7 ± 7.9	146.9 ± 14.2
Angle (º)	18 ± 6	20 ± 5	27 ± 6	25 ± 7	17 ± 4	17 ± 7	25 ± 6	23 ± 5
Velocity (°·s^{-1})	-306 ± 165	-329 ± 181	-419 ± 149	-375 ± 225	-278 ± 146	-222 ± 142	-413 ± 109	-376 ± 213
Initial Contact								
eccKF (Nm)	127.6 ± 10.5 95%CI: 10.9 to 23.6*	119.9 ± 7.6	110.3 ± 7.2	106.9 ± 5.3	129.0 ± 8.3 95%CI: 13.3 to 23.9*	133.6 ± 10.7 95%CI: 16.0 to 28.7*	110.4 ± 6.6	111.4 ± 6.4
Angle (º)	46 ± 7	43 ± 6	50 ± 6	51 ± 7	43 ± 4	43 ± 9	47 ± 6	47 ± 6
Velocity (°·s^{-1})	-106 ± 144	-181 ± 98	-137 ± 102	-81 ± 65	-94 ± 118	-178 ± 112	-119 ± 99	-135 ± 75
Loading Phase								
eccKF (Nm)	156.7 ± 9.6 95%CI: 12.0 to 26.6*	157.7 ± 11.0	138.9 ± 8.7	136.8 ± 16.1	153.5 ± 9.7 95%CI: 6.9 to 23.8*	151.3 ± 8.6	138.1 ± 14.0	133.0 ± 15.6
Angle (º)	47 ± 7	22 ± 4	30 ± 6	29 ± 8	19 ± 4	43 ± 9	26 ± 6	26 ± 6
Velocity (°·s^{-1})	-361 ± 167	-342 ± 188	-429 ± 147	-383 ± 240	-294 ± 141	-283 ± 171	-420 ± 107	-385 ± 219
Propulsive Phase								
eccKF (Nm)	151.3 ± 11.6	152.2 ± 9.4	148.0 ± 6.8	125.4 ± 9.7	150.7 ± 10.8*	148.0 ± 12.6	131.6 ± 7.3	130.4 ± 9.2

		95%CI: 20.0 to 33.5*	95%CI: 12.9 to 19.9** 18.7 to 25.6~		95%CI: 12.67 to 25.6*	95%CI: 9.92 to 25.39*		
conKE (Nm)	60.4 ± 34.1	54.5 ± 28.0	46.8 ± 19.0	57.2 ± 26.7	63.7 ± 33.2 95%CI: 21.8 to 16.5*	67.1 ± 33.7 95%CI: 2.0 to 43.8*	41.0 ± 20.1	44.2 ± 25.4
Angle (º)	26 ± 8	27 ± 6	33 ± 6	35 ± 6	22 ± 5	29 ± 10	29 ± 6	30 ± 6
Velocity ($°·s^{-1}$)	264 ± 174	313 ± 143	300 ± 107	256 ± 140	238 ± 165	251 ± 151	302 ± 109	294 ± 140

* symbol denotes a significant difference between playing age.
** symbol denotes significant difference between cutting manoeuvre, irrespective of age.
~ symbol denotes a significant difference between lower limbs.

Predicted Strength at Loading Phase

The GLM identified no significant interactions for age, limb and manoeuvre (*P* = 0.388; η^2 = 0.023); however a significant age and manoeuvre (*P* = 0.043; η^2 = 0.122) interaction was identified during both sidestep and crossover manoeuvres. Post-hoc analysis revealed that the senior females eccKF were significantly higher when compared to youth players (Table 9.2).

Predicted Strength at Propulsive Phase

The GLM identified a significant interaction for age, limb, manoeuvre and contraction type (*P* = 0.001; η^2 = 0.308) (Table 9.2). The senior females non-dominant eccKF during sidestep manoeuvres were significantly higher when compared to youth players. Additionally, both dominant and non-dominant limbs for eccKF and conKE were significantly higher in senior females when compared to youth players for crossover manoeuvres. It was also identified that youth females exhibited significantly higher eccKF values for the dominant limb during sidestep manoeuvres when compared to crossover manoeuvres. Moreover, youth females also exhibited significantly higher eccKF in the dominant limb when compared to the non-dominant limb during sidestep cutting manoeuvres.

9.4 Discussion

The purpose of this study was to develop predictive regression equations expressing strength as a function of knee joint angle and velocity in female soccer players. These models were subsequently used to quantify thigh musculature strength at knee joint angles and velocities related to key events of functionally challenging tasks across female soccer playing ages. It was identified that knee joint angles and velocities were significant predictors for eccKF and conKE strength specific to senior and youth female soccer players. Thereafter, the predictive regression equations identified no significant differences in predicted peak muscular strength of the eccKF and conKE during sidestep and crossover hopping manoeuvres between playing ages. However, when considering the initial ground contact, loading and propulsive phases of the hopping manoeuvres, senior females were able to elicit significantly higher thigh musculature strength values when compared to youths. It was also identified that youth female soccer players exhibited significantly higher eccKF values for the dominant limb when compared to the non-dominant side during the propulsive phase of sidestep hopping manoeuvres. The present data indicates youth female soccer players possess a reduced strength capacity of the thigh musculature when compared to senior aged players during hopping manoeuvres, and may predispose these players to an increased injury risk (Renstrom et al. 2008; Podraza and White, 2010; Waldén et al. 2016).

Since this is the first study to predict muscular strength during the completion of functional tasks, comparisons to previous literature are not possible. Nevertheless, these present findings are largely in agreement with study 4 of the thesis, which identified senior female soccer players to possess significantly higher thigh musculature strength values when compared to youth females. However, the present study was able to identify significant strength differences between female soccer playing ages during particular phases of hopping tasks, irrespective of sidestep and crossover manoeuvres. Specifically, it was identified that senior female soccer players exhibited significantly higher strength values when compared to youth players at 0.1 seconds following initial ground contact, and during the loading and propulsive phase of hopping manoeuvres. However, the present study also identified that peak predicted eccKF strength during the hopping manoeuvres were not significantly different between senior and youth female soccer players. As such, these data are in support of profiling strength beyond peak values to better determine differences between soccer playing ages. These events should be considered when screening for potential injury risk as it is suggested that thigh musculature and knee ligament injury risk is increased following initial ground contact of functional movements (Krosshaug et al. 2006; Hewett et al. 2009). Additional literature also suggests that the deceleration phase of functional movements also increases injury risk due to the requirement of the musculature to eccentrically contract and provide postural support (Shimokochi and Shultz, 2008; Boden et al. 2010; Podraza and White, 2010). However, hopping manoeuvres also places increased multiplanar demands upon the knee joint that are also associated with injury risk (Olsen et al. 2004; Pappas et al. 2007; Ortiz et al. 2011). As the change of direction component of hopping manoeuvres typically occur during the propulsive phase of movement (Quatman, Quatman-Yates and Hewett, 2010), sagittal and frontal plane knee biomechanics should also be used to determine the lower limb's ability to maintain postural control during this period.

The current data identified that senior female soccer players possess significantly higher eccKF strength when compared to youth players during sidestep and crossover hopping manoeuvres. These data could suggest that impaired eccKF strength during hopping manoeuvres for youth female soccer players may influence increased injury risk in this cohort of players (LeGall et al. 2008; Renstrom et al. 2008; Hartmut et al. 2010; Waldén et al. 2016). This is further supported by previous observations that identified thigh musculature strength deficits are associated with knee ligament injuries in youth females (Augustsson and Ageberg, 2017). The present study findings are also further supported by Manson et al. (2014) and study 4 of the thesis that identified significantly higher thigh musculature strength values in senior female soccer players when compared to youths. Furthermore, the youth players' non-dominant limb eccKF strength values were significantly lower when compared to the dominant side during the propulsive phase of sidestep hopping tasks. This may also be an additional factor that may influence the higher number of knee ligament injuries in the non-dominant limb of youth female soccer players (Negrete et al. 2007; Brophy et al. 2010; Hägglund and Waldén, 2016). When considering that sufficiently developed muscular strength is likely to reduce injury risk (Croisier et al. 2008; Augustsson and Ageberg, 2017; Lee et al. 2017), the lower strength values in youth female soccer players, in particular to the non-dominant limb, may influence the high injury incidence reported in this cohort of players. These findings may have particular implications for youth female soccer players who begin to compete against more senior and physically developed players that may place additional injury risk (Söderman et al. 2001; Van Der Sluis et al. 2015).

An additional aim of this study was to compare predicted muscular strength across sidestep and crossover hopping manoeuvres. The predicted strength values observed between sidestep and crossover tasks identified similar muscular strength requirements and demands for the thigh musculature. However, a significant difference did identify that youth female soccer player's eccKF values were higher during the concentric phase of sidestep manoeuvres when compared to crossover manoeuvres. These data suggest that the KF may have a reduced capacity to stabilise the knee joint during the change of direction phase of movements that place large multiplanar demands upon the knee joint (Quatman, Quatman-Yates and Hewett, 2010). However, it was not determined in this study whether these discrepancies were significantly higher in the KE moments when compared to the eccKF strength, and warrant future comparisons.

The present study identifies that predicted thigh musculature strength is comparable across sidestep and crossover tasks, and can be accounted by the knee joint angles and velocities exhibited during the completion of these tasks. When comparing between sidestep and crossover movements, the predicted strength values were comparable despite different knee joint angles and velocities. However, this can be accounted by the combined effect of knee joint angle and velocity. For instance, the regression analyses revealed that for the eccKF, the coefficient for joint angle identified lower strength values during increased knee flexion. When considering angular velocity, these results demonstrated gradual increases in strength with higher velocities. Therefore, by combining these responses, the predicted strength values for the sidestep tasks elicited increased angular velocity and knee flexion to that of crossover movement, and accounts for these similar strength values recorded during these movements. The combined effect of knee joint angle and velocity also account for the different predicted strength values that were observed across all defined events. For the eccKF, the observed higher strength values recorded during the loading phase when compared to initial ground contact can be attributed to the increased knee extension angles and angular velocities exhibited. This is can be accounted by the coefficients for knee joint angle and velocity, where these results indicate higher strength values for eccKF occur during periods of increased knee extension coupled with higher angular velocities.

The present data suggests knee joint angle and angular velocity, specific to soccer playing age and gender, are significant predictors of thigh musculature strength. These observations are further supported by section A of the thesis and previous isokinetic strength assessments that identified strength is influenced by knee joint angle and angular velocity (El-Askher et al. 2015; Cohen et al. 2015; Evangelidis et al. 2015; De Ste Croix et al. 2017). In order to calculate strength, the movement must exhibit similar knee angular velocities to those used during isokinetic strength assessments of the thigh musculature, and further advocates the use of hopping manoeuvres.

As it has been suggested that ACL injury risk is highest during and following 0.1 seconds following ground contact of functional tasks, the sampling frequency of 120Hz provides only 5 frames of footage to analyse during this period. As such, the camera sampling frequency used in this study may be a limitation, thus further research using higher sampling frequencies may be required in these populations to more appropriately identify injury risk. As injury risk may also be increases during movements with increases knee joint angular velocities, the use of hopping tasks could also considered a limitation. However, as hopping tasks resemble similar knee joint angular velocities to those observed during the assessment of isokinetic strength, this movement was able to quantify thigh musculature strength during the completion of these tasks. In turn, this may also reveal if the thigh musculature are possess appropriate strength values to dissipate the joint moments placed upon the knee.

9.5 Conclusion

This present study identified that knee joint angles and velocities were significant and strong predictors of thigh musculature strength. In turn, the predictive equations generated from the multiple linear regressions were able to quantify thigh musculature strength during sidestep and crossover hopping manoeuvres relative to female soccer playing age. Although peak muscular strength between playing ages were not significantly different, the use of age specific algorithms were able to identify differences across all phases of movement defined in this study. These equations yield data which enables a more functionally specific comparison of playing age at specific phases of movement. These approaches may also identify whether the moments placed upon the knee joint during the completion of functional tasks are disproportionate to the thigh musculature strength capacities of senior and youth female soccer players. In turn, this may place an increased demand of the thigh musculature to dissipate large impact forces and may further influence injury risk, and will be explored in part two of this study.

CHAPTER 10

A Comparison of Predicted Thigh Musculature Strength and Knee Joint Moments in Female Soccer Players

10.1 Introduction

The first part of the final study identified no significant differences between senior and youth female soccer players in predicted peak thigh musculature strength during sidestep and crossover hopping manoeuvres. However, when specific phases of movement where considered, the senior females were able to elicit significantly higher predicted eccKF and conKE strength values when compared to youth players. These approaches may be able to identify whether the thigh musculature are sufficiently developed to dissipate the moments placed upon the knee joint during functional tasks at specific phases of movement. The present study focussed on identifying whether knee joint moments elicited during hopping manoeuvres were disproportionate to the thigh musculature's strength capacity in senior and youth female soccer players.

Biomechanical assessments identify that exacerbated knee abduction and KE moments are associated with increased risk of knee ligament injury (Hewett et al. 2005; Shimokochi et al. 2009; Hewett et al. 2010; Leppänen et al. 2017). In turn, this places an increased demand of the KF to counteract large joint moments (Doorenbosch and Harlaar 2003; Kellis et al. 2003). This has consequently led to literature suggesting that functional movements that exhibit large KE moments are associated with increased risk of knee ligament injury (Myer et al. 2004, 2009; Hewett et al. 2010). However, further research also identifies that KE moments are highest at knee joint angles of ~70° of knee flexion (Podraza and White, 2010), and not indicative of a KE dominance where injury reportedly occurs (Boden and Dean, 2000; Olsen et al. 2004; Pappas et al. 2007). As a consequence, this has led to suggestions that sufficiently developed strength of the KE musculature are also required to dissipate large moments placed on the knee joint (Norcross et al. 2010; Podraza and White, 2010). As such, if the external moments placed upon the knee joint are disproportionately higher than the musculature strength capacity, this may place increased demands to maintain postural control and dissipate large impact forces. Sufficiently developed muscular strength of both KF and KE are therefore required to provide dynamic support for the knee joint during different phases of functional tasks (Hughes and Watkins, 2006).

The procedures outlined in the previous study are able to quantify thigh musculature strength during initial ground contact, loading and propulsive phases of hopping manoeuvres that are suggested to be associated with increased injury risk (Quatman, Quatman-Yates and Hewett, 2010; Hewett and Myer, 2011; Norcross et al. 2013). As such, these approaches may better determine strength, as outlined in the thesis, at arbitrary knee joint angles and velocities associated with these tasks. The prediction of thigh musculature strength during hopping tasks also identified youth female soccer players to possess a reduced predicted strength capacity of the thigh musculature in comparison to their senior counterparts at the aforementioned phases of movement, and may be indicative of increased injury risk. Moreover, the previous study identified youth females to possess significantly lower non-dominant limb eccKF strength when compared to the dominant side, thus these musculature may have a reduced capacity to counter large KE moments during functional tasks and predispose this limb to an increased injury risk (Brophy et al. 2010; Hägglund and Waldén, 2015). When considering the combination of knee biomechanics and predicted thigh musculature strength during the completion of functional tasks, youth female soccer players may also have an increased demand to maintain postural control and dissipate impact forces at the aforementioned phases of movement, in particular for the non-dominant limb (Hewett et al. 2004; Hewett et al. 2015).

As advocated by the thesis, the assessment of sidestep and crossover hopping manoeuvres can be used to assess knee biomechanics and predict thigh musculature strength values. To identify whether senior and youth female soccer players' thigh musculature strength are proportionate to the moments placed upon the knee joint during hopping manoeuvres, this study will provide additional analyses on the respective data from the previous experimental chapter. The aims of part two of the final study were twofold: (a) to identify whether predicted eccKF and conKE were significantly different to the knee joint moments exhibited during the completion of hopping manoeuvres, relative to female soccer playing age, lower limb, and manoeuvre, (b) to compare the sagittal and frontal plane knee joint moments between senior and youth female soccer players, relative to lower limb and manoeuvre.

10.2 Methods

Participants

Participants identified in the previous experimental chapter were selected for this present study.

Testing Procedures

The testing procedures comprised the completion of the procedures previously described in studies the general methods section.

Data Analysis

Data analysis was conducted utilising the same procedures as previously described in the general methods section.

Statistical Analysis

To establish whether statistically significant differences existed between the senior and youth playing ages, a repeated measures GLM was performed. The assumptions associated with a repeated GLM were assessed to ensure model adequacy. To assess residual normality for each dependant variable, q-q plots were generated using stacked standardised residuals. Scatterplots of the stacked unstandardised and standardised residuals were also utilised to assess the error of variance associated with the residuals. Mauchly's test of sphericity was also completed for all dependent variables, with a Greenhouse Geisser correction applied if the test was significant. Where significant main effects or interactions were observed, post hoc pairwise comparisons with a Bonferonni correction factor were applied with 95% CI for differences were also reported. Partial eta squared (η^2) values were calculated to estimate effect sizes for all significant main effects and interactions. Partial eta squared was classified as small (0.01 to 0.059), moderate (0.06 to 0.137) and large (>0.138) (Cohen, 1988). All statistical analysis was completed using PASW Statistics Editor 22.0 for windows (SPSS Inc, Chicago, USA). Statistical significance was set at $P \leq 0.05$.

10.3 Results

Peak Knee Extensor Moments

As identified by Figure 10.1, no significant interactions were identified for age, limb, and manoeuvre ($P = 0.802$; $\eta^2 = 0.002$), age and manoeuvre ($P = 0.147$; $\eta^2 = 0.064$), nor age and limb ($P = 0.992$; $\eta^2 < 0.001$). There was also no significant main effect for manoeuvre ($P = 0.711$; $\eta^2 = 0.004$) whereas a significant main effect for limb identified higher peak KE moments in the dominant limb (195.08 ± 44.49Nm) when compared to the non-dominant limb (174.85 ± 48.38Nm; 95% CI: 8.65 to 31.79Nm).

Initial Contact

The GLM identified no significant interactions for age, limb, and manoeuvre ($P = 0.688$; $\eta^2 = 0.005$), age and manoeuvre ($P = 0.308$; $\eta^2 = 0.0532$), nor age and limb (*P*

= 0.289; $\eta^2 = 0.035$). There were also no significant main effects for limb ($P = 0.102$; $\eta^2 = 0.081$), whereas a significant manoeuvre main effect ($P = 0.003$; $\eta^2 = 0.251$) identified higher KE moments in sidestep (172.08 ± 44.87Nm) when compared to crossover trials (148.45 ± 43.60Nm; 95% CI: 8.91 to 38.33Nm).

Loading Phase

The GLM identified no significant interactions for age, limb, and manoeuvre (P = 0.098; $\eta^2 = 0.083$), age and manoeuvre ($P = 0.270$; $\eta^2 = 0.038$), nor age and limb (P = 0.631; $\eta^2 = 0.007$). A significant main effect for limb ($P < 0.001$; $\eta^2 = 0.336$) identified higher KE moments in the dominant limb (46.07 ± 38.17Nm) when compared to the non-dominant limb (30.91 ± 41.68Nm; 95% CI: 7.48 to 22.83Nm). A significant main effect for manoeuvre ($P < 0.001$; $\eta^2 = 0.494$) also identified higher peak KE moments in sidestep trials (51.83 ± 38.35Nm) when compared to crossover trials (25.14 ± 41.50Nm; 95% CI: 16.97 to 36.40Nm).

Propulsive Phase

The GLM identified no significant interactions for age, limb, and manoeuvre (P = 0.686; $\eta^2 = 0.005$), age and manoeuvre ($P = 0.177$; $\eta^2 = 0.056$), nor age and limb (P = 0.590; $\eta^2 = 0.009$). There was no significant main effect for manoeuvre ($P = 0.123$; $\eta^2 = 0.073$), whereas a significant main effect for limb ($P = 0.003$; $\eta^2 = 0.238$) identified higher KE moments in the non-dominant limb (39.76 ± 31.74Nm) when compared to dominant limb (29.30 ± 26.69Nm; 95% CI: 3.72 to 17.19Nm).

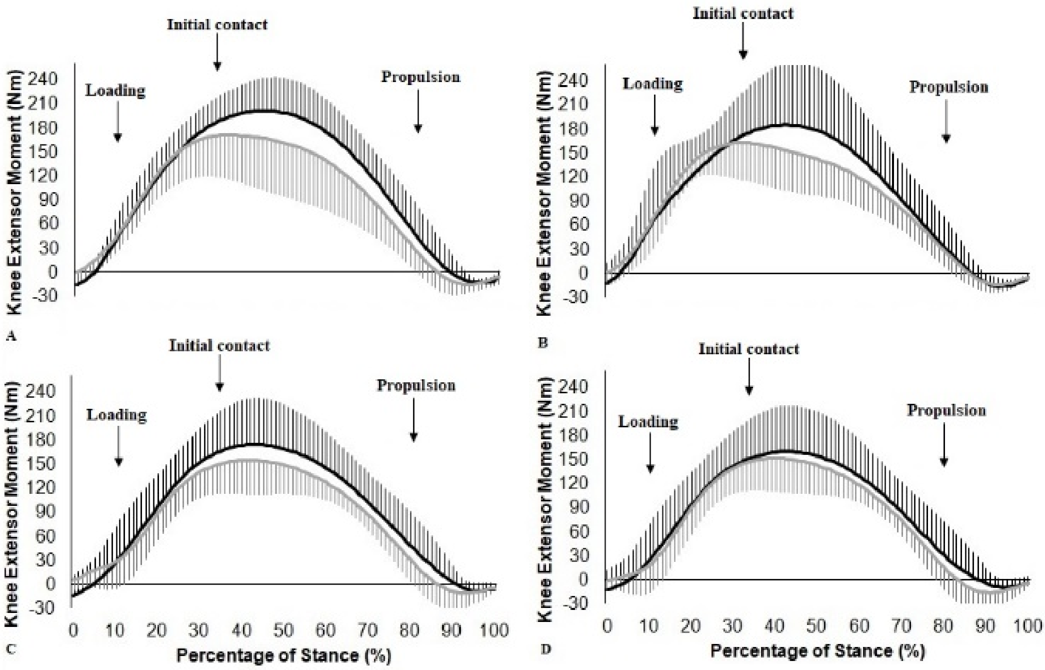

Figure 10.1 illustrates KE moments during the stance phase of hopping manoeuvres for senior (black) and youth (grey) players. A: dominant sidestep; B: non-dominant sidestep; C: dominant crossover; D: non-dominant crossover.

Peak Knee Abduction Moments

As identified by Figure 10.2, a no significant interactions were identified for age, limb, and direction (P = 0.871; η^2 = 0.001), age and direction (P = 0.872; η^2 = 0.001), nor age and limb (P = 0.170; η^2 = 0.058). A significant main effect for limb (P = 0.007; η^2 = 0.206) identified higher peak knee abduction moments in the dominant limb (-75.02 ± 34.41Nm) when compared to the non-dominant limb (-61.76 ± 36.57Nm; 95% CI: -3.90 to -122.67Nm). A significant main effect for the direction of the manoeuvre (P < 0.001; η^2 = 0.815) also identified higher peak knee abduction moments in crossover (-106.91 ± 24.1 Nm) when compared to sidestep trials (-30.71 ± 46.85 Nm; 95% CI: -62.43 to -82.32Nm).

Initial Contact

The GLM identified no significant interactions for age, limb, and direction (P = 0.735; η^2 = 0.004), age and direction (P = 0.692; η^2 = 0.005), nor age and limb (P = 0.647; η^2 = 0.0107). No significant main effect for limb (P = 0.084; η^2 = 0.091) was identified, whereas a significant main effect for the direction of the manoeuvre (P < 0.001; η^2 = 0.769) identified higher knee abduction moments in crossover trials (-74.83 ± 38.27Nm) when compared to sidestep trials (-14.01 ± 31.47Nm; 95% CI: -48.83 to -72.81Nm).

Loading Phase

The GLM identified no significant interactions for age, limb, and direction (P = 0.860; η^2 = 0.001), age and direction (P = 0.413; η^2 = 0.021), age and limb (P = 0.699; η^2 = 0.005). A significant main effect for limb (P = 0.005; η^2 = 0.223) identified higher knee abduction moments in the dominant limb (-32.49 ± 24.45Nm) when compared to the non-dominant limb (-21.12 ± 21.94Nm; 95% CI: -3.72 to -19.01Nm). A significant main effect for the direction of the manoeuvre (P < 0.001; η^2 = 0.640) also identified higher peak knee abduction moments in crossover trials (-36.70 ± 23.27Nm) when compared to sidestep trials (-16.90 ± 23.12Nm; 95% CI: -14.45 to -25.13Nm).

Propulsive Phase

The GLM identified no significant interactions for age, limb, and direction (P = 0.664; η^2 = 0.006), age and direction (P = 0.753; η^2 = 0.003), nor age and limb (P = 0.736; η^2 = 0.004). There was no significant main effect for limb (P = 0.199; η^2 = 0.051), whereas a significant main effect for direction (P < 0.001; η^2 = 0.748) identified higher knee abduction moments in the crossover manoeuvres (-39.77 ± 28.06Nm) when compared to the sidestep trials (-6.68 ± 18.08Nm; 95% CI: -26.16 to -40.00Nm).

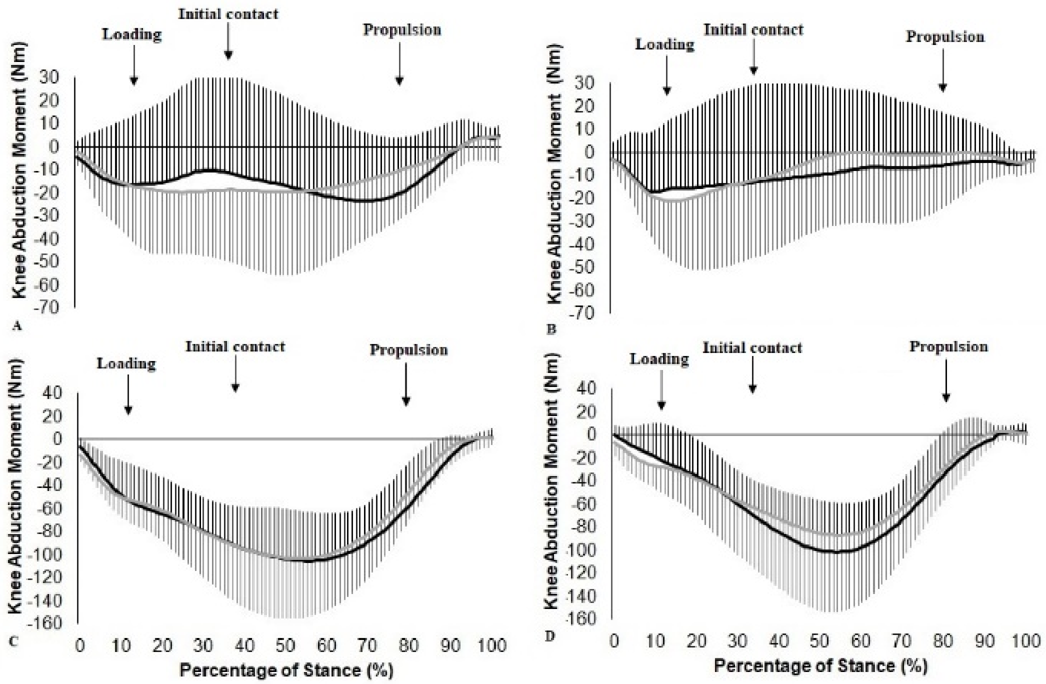

Figure 10.2 illustrates knee abduction moments during the stance phase of hopping manoeuvres for senior (black) and youth (grey) players. A: dominant sidestep; B: non-dominant sidestep; C: dominant crossover; D: non-dominant crossover.

Strength and Joint Moment Comparisons

Initial Ground Contact

The GLM identified a significant four-way interaction for age, manoeuvre, limb and moments (P = 0.032; η^2 = 0.126). As demonstrated by Table 10.1, it was identified in senior females that the KE moments were significantly higher in sidestep and crossover manoeuvres for the dominant lower limb when compared to the predicted eccKF values. Similar findings were also observed for the non-dominant limb, as KE moments were significantly higher in sidestep, but not crossover manoeuvres when compared to the predicted eccKF values. For youth female soccer players, it was identified that the KE moments were significantly higher in sidestep and crossover manoeuvres for the dominant lower limb when compared to the predicted eccKF values. Similar findings were also observed for the non-dominant limb, as the KE moments were significantly higher in sidestep and crossover manoeuvres when compared to the predicted eccKF values.

Loading Phase

The GLM identified a significant four-way interaction for age, manoeuvre, limb and moments (*P* = 0.017; $\eta^2 = 0.135$). As demonstrated by Table 10.1, it was identified in senior females that the predicted eccKF values were significantly higher in sidestep and crossover manoeuvres for the dominant lower limb when compared KE moments. Similar findings were also observed for the non-dominant limb, as the predicted eccKF values were significantly higher in sidestep and crossover manoeuvres when compared to KE moments. For youth female soccer players, it was identified that the predicted eccKF values were significantly higher in sidestep and crossover manoeuvres for the dominant lower limb when compared to KE moments. Similar findings were also observed for the non-dominant limb, as the predicted eccKF values were significantly higher in sidestep and crossover manoeuvres when compared to KE moments.

Propulsive Phase

The GLM identified a significant four-way interaction for age, manoeuvre, limb, and moments (*P* = 0.048; $\eta^2 = 0.093$). As demonstrated by Table 10.1, it was identified in senior females that the predicted conKE values were significantly higher in sidestep, but not for crossover manoeuvres, for the dominant lower limb when compared to KE moments. For the non-dominant limb, the predicted conKE values were not significantly higher in sidestep, but were during crossover manoeuvres when compared to KE moments. For youth female soccer players, it was identified that the predicted conKE values were significantly higher in sidestep and crossover manoeuvres for the dominant lower limb when compared to KE moments. For the non-dominant limb, the predicted conKE values were not significantly higher in sidestep, but were during crossover manoeuvres when compared to KE moments.

Table 10.1
KE Moments and Predicted Thigh Musculature Strength Between Senior and Youth Females During Sidestep Manoeuvres. 95% CI for Differences are Reported for all Significant Differences

	Senior		**Youth**		**Senior**		**Youth**	
	Sidestep Manoeuvre				Crossover Manoeuvre			
	Dominant	Non-dominant	Dominant	Non-dominant	Dominant	Non-dominant	Dominant	Non-dominant
Initial Contact (Nm)								
Internal Net Moment	189.3 ± 49.9* 95%CI: 46.8 to 98.5	168.2 ± 49.8* 95%CI: 24.2 to 86.8	168.2 ± 34.8* 95%CI: 30.8 to 81.8	162.4 ± 43.7* 95%CI: 13.5 to 76.1	155.5 ± 43.5* 95%CI: 43.4 to 92.7	145.0 ± 55.4	147.1 ± 34.3* 95%CI: 23.2 to 72.7	146.0 ± 41.8* 95%CI: 12.1 to 65.9
Predicted eccKF	127.6 ± 10.5	119.9 ± 7.6	110.3 ± 7.2	106.9 ± 5.3	129.0 ± 8.3	133.6 ± 10.7	110.4 ± 6.6	111.4 ± 6.4
Loading Phase (Nm)								
Internal Net Moment	63.1 ± 46.6	20.4 ± 36.9	73.3 ± 31.1	50.4 ± 32.4	16.0 ± 39.3	24.8 ± 61.9	31.7 ± 33.7	27.9 ± 23.0
Predicted eccKF	156.7 ± 9.6* 95%CI: 5.4 to 111.8	157.7 ± 11.0* 95%CI: 116.2 to 149.9	138.9 ± 8.7* 95%CI: 47.4 to 83.8	136.8 ± 16.1* 95%CI: 70.7 to 104.5	153.5 ± 9.7* 95%CI: 121.8 to 161.5	151.3 ± 8.2* 95%CI: 106.0 to 151.4	138.1 ± 14.0* 95%CI: 85.2 to 124.9	133.0 ± 15.6* 95%CI: 87.4 to 132.8
Propulsive Phase (Nm)								
Internal Net Moment	29.5 ± 30.8	51.2 ± 39.4	24.1 ± 19.5	45.3 ± 21.5	38.2 ± 39.6	41.0 ± 40.8	25.3 ± 27.8	21.4 ± 15.6

Predicted conKE	60.4 ± 34.1* 95%CI: 11.6 to 50.1	54.5 ± 28.0	46.88 ± 19.0	57.2 ± 26.7	63.7 ± 33.2	67.1 ± 33.7	41.0 ± 20.1	44.2 ± 25.4

The (*) symbol denotes a significant difference between net internal moments and predicted thigh musculature strength

10.4 Discussion

The present data identified no significant differences between female soccer playing ages in sagittal and frontal plane knee joint moments, although significantly higher knee abduction moments were identified for the crossover tasks and dominant limb. Further observations also identified significantly higher KE moments during initial ground contact of hopping manoeuvres, relative to playing age, lower limb, and cutting manoeuvre, when compared to predicted eccKF strength values. During the loading and propulsive phases of hopping manoeuvres, significantly higher predicted eccKF and conKE strength values, respectively, were identified when compared to KE moments. These present data consequently suggest the KE moments exhibited during the initial contact phase of hopping manoeuvres are disproportionate to the strength capacities of the eccKF in female soccer players. As such, the predicted eccKF musculature have a reduced ability to counteract large KE moments during the completion of functional tasks where injury risk is reportedly increased (Hewett and Myer, 2011; Benche et al. 2012; Norcross et al. 2013).

Irrespective of playing age and direction of cutting manoeuvre, the present study identified significantly higher peak knee abduction moments for the dominant limb when compared to the non-dominant side. These findings were also consistent for the dominant limb's peak KE moments and respective values recorded at initial ground contact. No significant differences were also identified between lower limbs for knee abduction moments following initial ground contact where risk of knee ligament injuries are increased (Hewett and Myer, 2011; Benche et al. 2012; Norcross et al. 2013). Similar findings for knee abduction moments also identified no significant differences between lower limbs at the loading and propulsive phases of hopping manoeuvres. Furthermore, the present study identified significantly higher knee abduction moments for crossover tasks when compared to sidestep trials, in agreement with some (Malinzak et al. 2001; Harrison et al. 2008; Ortiz et al. 2011), but not all (Besier et al. 2001; Potter et al. 2014) previous studies. These present findings therefore reinforce the need to consider different manoeuvres and phases of movement to appropriately inform preventative measures.

Previous studies have compared between sidestep and crossover cutting manoeuvres, with some (Besier et al. 2001; Potter et al. 2014) but not all (Malinzak et al. 2001) identified significantly higher knee abduction and extensor moments in sidestep manoeuvres. The present study identified significantly higher knee abduction moments during sidestep manoeuvres when compared to crossover tasks, in agreement with some previous observations (Besier et al. 2001; Potter et al. 2014). However, the present study is not entirely in support with these previous observations as significantly higher knee abduction moments were identified during crossover tasks, and may be accounted by increased medial impact forces elicited during these tasks (Jindrich et al. 2006). These present findings are however in agreement with the observations of Ortiz et al. (2011) that identified significantly higher knee abduction moments in non-injured healthy females during crossover hopping when compared to sidestep tasks. As change of direction tasks commonly use sidestep manoeuvres to determine sagittal and frontal plane knee biomechanics (Brown et al. 2014), disregarding the use of crossover manoeuvres may overlook large knee abduction moments elicited. This may have implications for injury risk given the association between exacerbated knee abduction moments and knee ligament injury (Hewett et al. 2005; Shimokochi et al. 2009), thus there appears a need to screen for both sidestep and crossover tasks.

These present data also reveal that the knee abduction and extensor moments varied throughout all defined events. In relation to knee extensor moments, these values were highest around the period following initial ground contact, where knee flexion angles would begin to increase. This is a result of an external knee flexor moment that flexes the knee joint, thus an equal and opposite internal extensor moment is required to oppose these external forces (Brunner and Rutz, 2013). This is also in support of further research that identified higher knee extensor moments at increased knee flexion angles during bilateral drop landings (Podraza and White, 2010; Norcross et al. 2013). For knee abduction moments, these values were also highest around the period following initial ground contact where the directional change begins to occur. These responses may be attributed to a longer moment arm during directional changes, where increased horizontal placement of the lower limb has been suggested to increase the perpendicular distance between the knee joint and force vector, resulting in increased knee abduction moments typically seen in multiplanar movements (Quatman et al. 2010; Jones et al. 2015). In turn, this may place demands of the thigh musculature to dissipate this forces and maintain postural control.

As no study to date has previously considered thigh musculature strength capacities in relation to the moments placed upon the knee joint during functional tasks, direct comparisons to previous literature are not possible. Nevertheless, biomechanical parameters, such as KE moments have been associated with increased risk of knee ligament injury (Shimokochi et al. 2009; Hewett et al. 2010; Leppänen et al. 2017), yet considering this metric in isolation without the appreciation the thigh musculature's ability to manage these demands may not be appropriate. This is further supported by previous suggestions that identified sufficiently developed eccKF strength is required to help provide dynamic stability for the knee joint by resisting large KE moments during the completion of functional tasks (Doorenbosch and Harlaar 2003;

Kellis et al. 2003; Hughes and Watkins, 2006). Similarly, the KE are also required to dissipate large impact forces during functional movements associated with risk of knee ligament injury (Norcross et al. 2010; Podraza and White, 2010). However, as the aforementioned literature did not determine thigh musculature strength, it is unclear as to whether strength deficits relative to the KE moments may be an influencing factor for risk of knee ligament injury. The present data identified at initial ground contact that the KE moments were significantly higher when compared to predicted eccKF strength values, irrespective of playing age, manoeuvre and limb. These data therefore advocate the assessment of net joint moments relative to strength of the thigh musculature during functional movements.

The present data identified that the KE moments following initial ground contact were significantly higher when compared to predicted eccKF strength values, irrespective of hopping manoeuvre, thus placing these musculature at an increased demand to provide dynamic stability for the knee joint (Doorenbosch and Harlaar 2003; Kellis et al. 2003). It has also been reported that knee ligament injury risk is largest following initial ground contact, and reinforces the need to determine knee biomechanics across specific events during the completion of functional tasks (Hewett and Myer, 2011; Norcross et al. 2013). As such, these findings also reiterate the need for sufficiently developed eccKF strength during specific phases of functional movements associated with injury risk (Shimokochi and Shultz, 2008; Boden et al. 2010). In contrast, during the loading and propulsive phases of hopping manoeuvres, the predicted eccKF and conKE strength values, respectively, were significantly higher when compared to the KE moments. These present observations support the need to develop preventative strategies that better conditioning soccer players to manage the large demands placed upon the knee joint following initial ground contact.

The significant differences between KE moments and predicted eccKF muscular strength at initial ground contact were further pronounced in youth female soccer players when compared to seniors, irrespective of hopping manoeuvres. These observations are accounted by the present study findings that identified no significant differences in KE moments between female soccer ages during hopping manoeuvres. In addition, youth female soccer players possessed significantly reduced predicted eccKF strength values when compared to senior aged players during the completion of crossover hopping manoeuvres at initial ground contact, as identified by the previous experimental chapter. Therefore, youth female soccer player's eccKF may be at an increased demand to provide knee joint stability, as previously described. These present observations may have implications for youth female soccer players who are predisposed to an increased risk of knee ligament injury (Renstrom et al. 2008; Hägglund and Waldén, 2016). Biomechanical screening methods that determine KE moments should also consider the strength capacity of the thigh musculature to more appropriately identify discrepancies that may influence potential injury risk.

As the thesis has only assessed eccKF and conKE, the present study was unable to refer to eccentric KE strength, and acknowledged as a limitation, therefore research should also determine these strength values in future research. Moreover, the algorithms used to predict thigh musculature strength are specific to data obtained throughout the thesis. These data are also specific to the populations used within this study, and cannot be generalised beyond this cohort of players. As such, further research may wish to conduct similar investigations in other populations. These data are able to suggest that the current procedures could better determine whether thigh musculature strength are sufficiently developed to dissipate the moments placed upon the knee joint, thereby better informing injury risk and exercise prescription.

Since the predicted strength values recorded in part one of this study occurred during the initial contact phase of movement where injury risk is suggested to be highest, these data may be indicative of an increased risk of injury to these cohorts of players. Section two of this study also identify that the knee extensor moments recorded at initial contact were disproportionately higher when compared to the eccKF, suggesting KE dominance at initial ground contact, which has also been previously associated with injury risk. To reduce potential risk of knee ligament injuries, it has been suggested that neuromuscular training programmes lower injury risk (Myer et al. 2013; Sugimoto et al. 2012; 2016). These training programmes comprise plyometric, strengthening, proprioceptive and verbal feedback, and were suggested by the aforementioned studies to be most effective when used in combination for at least 20 minutes, twice a week (Sugimoto et al. 2012; 2016). These training interventions could also be adapted in line with this study's findings by focusing plyometric movements that focus on initial ground contact of multidirectional tasks. This could also be combined with eccKF exercises that strengthen these musculature at specific knee joint angles and velocities. Therefore, functional (variants of deadlifts, squats and lunges) and isolated strengthening exercises for the knee flexors and knee extensors may be adapted to target strength developments at specific joint angles. Performing the aforementioned exercises at higher training velocities should consequently also be considered to improve force production during high-speed movements (Kawamori and Newton, 2006), and can also be adapted to target specific joint angles.

10.5 Conclusion

When determining the KE moments required during the completion of functional tasks, these parameters should be considered alongside the strength capacity of the thigh musculature. It was identified that the predicted eccKF and conKE strength values were significantly higher than KE moments elicited during the loading and propulsive phases of hopping manoeuvres, respectively. At initial ground contact, the present approaches were also able to identify that the KE moments were significantly higher than eccKF's strength capabilities, thus creating potential imbalances between these musculature which has been previously associated with injury risk (Croisier et al. 2008; Hewett et al. 2010; Leppänen et al. 2017; Lee et al. 2017). In turn, these approaches may identify additional training needs of soccer players aimed to reduce potential injury risk through appropriate interventions that include plyometric and strength training with real-time feedback (Myer et al. 2013; Sugimoto et al. 2012; 2016).

SECTION B SUMMARY

Angle and velocity specific measures of isokinetic strength are advocated for determining thigh musculature strength in soccer players. However, this methodological approach should aim to quantify muscular strength at precise knee joint angles and velocities that are exhibited during functional tasks associated with lower limb injury. It was identified that youth female's peak knee flexion angles were significantly higher for both lower limbs during sidestep tasks when compared to senior females. No other significant differences were identified for peak values associated in the sagittal and frontal planes between female soccer playing ages. When further events were considered, senior female soccer players exhibited significantly higher knee abduction angles during the loading phase of sidestep hopping manoeuvres when compared to youths. As such, the present findings identified limited differences in sagittal and frontal plane knee kinematics between senior and youth female soccer players during periods where injury risk is enlarged.

The results from study 5 also identified the knee joint angles and velocities exhibited during the completion of hopping tasks were similar to those observed in isokinetic dynamometry. These key events were subsequently used to predict thigh musculature strength, based on regression models expressing torque as a function of knee joint angle and velocity in study 6. Using the procedures defined in Section A of the thesis to determine thigh musculature strength, it was identified that knee joint angle and velocity were significant predictors of eccKF and conKE strength in senior and youth female soccer players. This subsequently allowed the prediction of thigh musculature strength by utilising knee joint angles and velocities exhibited during hopping manoeuvres. Thereafter, peak predicted musculature strength were not significantly different between senior and youth female soccer players. When considering initial contact, loading and propulsive phases of hopping manoeuvres, the predicted muscular strength values were significantly higher for the senior female soccer players when compared to youths, irrespective of hopping direction. It was also identified that youth female soccer players exhibited significantly higher eccKF strength in the dominant limb when compared to the non-dominant limb during sidestep hopping tasks. As such, these findings identify that youth female soccer players possess significantly lower thigh musculature strength values during periods where injury risk is reportedly increased.

The final study of this Section comprised further analyses of the data collected in study 6, and designed to identify if predicted thigh musculature strength were proportionate to the moments placed upon the knee joint during hopping manoeuvres. Study 7 identified that the knee joint moments exhibited during sidestep and crossover hopping manoeuvres were significantly higher when compared to the predicted thigh musculature strength during initial contact, but significantly lower at loading and propulsive phases of movement. These data also identified no significant differences in sagittal and frontal plane knee joint moments during hopping tasks between playing age. However, at all defined phases of movement, study 6 identified significantly lower thigh musculature strength values in youth female soccer players when compared to their senior counterparts. As such, youth female soccer players may experience a higher relative demand to maintain postural control and dissipate large impact forces, and may influence potential injury risk.

The collection of studies comprised within Section B of the thesis identified few differences in sagittal and frontal plane knee biomechanics between senior and youth female soccer players. These observations were also consistent across different phases of movement that have been previously associated with increased injury risk. As such, these data suggest that these cohorts of players predominately exhibit similar movement patterns. However, youth female soccer players elicited significantly lower thigh musculature strength values at the same defined phases of movement when compared to senior aged players. When considering that knee joint moments were not significantly different between female soccer playing ages, it could be suggested that youth females may experience a higher relative demand to maintain postural control and dissipate large impact forces. The collection of these studies may further develop strength profiling by calculating strength at specific phases of movements associated with injury risk, and evaluate these interpretations against the moments placed upon the knee joint.

CHAPTER 11

GENERAL DISCUSSION

11.1 Summary of Study Findings

The overall aim of the thesis was to further develop the procedures and analytical approaches of determining thigh musculature strength and methods for screening potential injury risk in elite cohorts of soccer players. For instance, the strength characteristics of the thigh musculature were influenced by the inclusion of knee joint angles and additional testing velocities. As such, the inclusion of these additional parameters have implications for identifying potential injury risk and subsequent exercise prescription. These additional procedures and analytical approaches were modifiable during late stage rehabilitation programme that could be equally be transferred to further exercise prescription. Age and gender of the soccer player also influence the angle and velocity specific measures of thigh musculature strength, thus screening methods are also warranted in these cohorts of players to identify potential injury risk and for informing subsequent exercise prescription.

11.2 General Discussion

Enlarged conKE strength values relative to the eccKF have been frequently identified by literature to be a risk factor for KF and ACL injuries (Croisier et al. 2002, 2008; Hewett et al. 2010; Lee et al. 2017). However, the aforementioned studies identified higher conKE strength values relative to the eccKF at low testing velocities and calculated DCR based on the PT of these musculature, despite APT occurring at distinctly different knee joint angles (Small et al. 2010; El-Ashker et al. 2015; De Ste Croix et al. 2017). Contrary to these suggestions, Section A of the thesis consistently demonstrated the eccKF were significantly stronger than the conKE musculature at increased knee joint angles and velocities where KF and ACL injuries are reported to occur (Boden and Dean, 2000; Chumanov et al. 2012; Higashihara et al. 2015). Significantly higher conKE values relative to the eccKF musculature were only identified at lower testing velocities at increased knee flexion angles, where injury risk is less likely to occur. Alternatively, the present procedures and metrics further reiterates the importance of the eccKF to stabilise the knee joint (Li et al. 1999; MacWilliams et al. 1999; Chmielewski et al. 2002) due to the inability of the KE to exhibit force where injury risk is increased. As such, the sole use of PT and DCR at low angular velocities that are consistently used may be inappropriate for identifying strength characteristics of eccKF and conKE with implications for injury risk. In turn, this may incorrectly identify conKE strength dominance when profiling these musculature in different cohorts of soccer players.

The defined procedures and metrics associated with isokinetic dynamometry were also sensitive to injury status, playing age and gender of the soccer player. Specifically, it was identified that eccKF and conKE PT, DCR and their angle-specific derivatives were modifiable following an appropriate training stimulus. Furthermore, these metrics were able to distinguish between injured and non-injured soccer players. Whilst the AST strength values also identified significant differences between soccer playing ages for both genders, the PT and DCR metrics were unable to identify significant differences in male soccer playing ages. However, it was identified that PT strength values for youth females were significantly lower when compared to their senior counterparts. Therefore, PT and DCR metrics may be more appropriate for identifying discrepancies between injured players and those with different weekly training demands. These observations are supported by previous studies in soccer players of varying ages, and identified larger differences in PT and DCR values between those with different training requirements (Gür et al. 1999; Kellis et al. 2001; Manson et al. 2014). However, AST measures are able to identify significant differences between male senior and youth players who have similar weekly training demands. As these metrics are not commonly determined during isokinetic strength assessments in senior or youth soccer players, disregarding these measures may lead to incorrect interpretation of training needs, particularly in those with increasingly subtle differences. As such, AST strength measures determined across different testing velocities may identify additional training needs of youth soccer players, and may be particularly important when considering these cohorts are predisposed to an increased injury risk (LeGall et al. 2006, 2008; Renshaw and Goodwin, 2016; Augustsson and Ageberg, 2017).

A limited number of significant differences were identified between senior and youth soccer players, relative to gender, for the DCR and DCR_{AST} metrics. These observations could indicate that youth soccer players may not be at an increased injury risk when compared to their senior counterparts. Nevertheless, to appropriately identify injury risk and inform exercise prescription, DCR and DCR_{AST} should be used in conjunction with their associated PT and AST values. Such considerations may be important for practitioners when considering that equally impaired strength of both eccKF and conKE can present DCR values of ~1, thereby suggesting muscular balance and a reduced risk of injury. Therefore, the corresponding torque values that calculate strength ratios are also recommended to identify both musculature strength deficits and imbalances, thus providing a more appropriate method of identifying training needs. These findings are particularly important as AST for the eccKF and conKE were significantly lower for youths when compared to senior aged players, thus the sole use of DCR_{AST} may not appropriately identify potential injury risk and training needs. These considerations therefore highlight limitations in recent prospective studies that identified no significant association with DCR's and KF injuries in soccer players (Dauty et al. 2017; Van Dyk et al. 2017); however, these findings may be attributed to the disregard of isokinetic torque.

The AST strength measures were also able to identify significant differences between dominant and non-dominant limbs that were not detected by the PT metric. Specifically, significantly higher eccKF AST values at 270°·s^{-1} were identified in senior male soccer players at increased knee extension angles for the dominant limb when compared to the non-dominant side. Moreover, significantly lower AST eccKF strength values were identified at increased knee extension angles and across velocities in youth female's non-dominant limb when compared to the dominant side. However, no significant differences were observed between dominant and non-dominant lower limbs for PT of the thigh musculature for these cohorts of players, thus AST may provide further insight into bilateral strength differences. Although previous studies have not assessed bilateral strength differences in female soccer players, such studies in males have yielded equivocal results when identifying PT between dominant and non-dominant lower limbs (Rahnama, Less and Bambaecichi, 2005; Croisier et al. 2008; Fousekis, Tsepis and Vagenas, 2010). Since these studies did not determine AST strength values, significant bilateral strength differences could have been overlooked. In turn, the defined procedures and metrics may further inform exercise prescription to correct for such discrepancies and reduce potential injury risk.

Defining AST metrics across angular velocities are advocated for identifying thigh musculature strength that better appreciates functional movements and mechanisms associated with injury (Boden and Dean, 2000; El-Ashker et al. 2015; Chumanov et al. 2012; Cohen et al. 2015; Evangelidis et al. 2015; Higashihara et al. 2015; De Ste Croix et al. 2017). However, these approaches can only determine thigh musculature strength characteristics of knee joint angles and velocities that are arbitrarily selected. In turn, it is not possible to identify the strength characteristics of the thigh musculature at precise knee joint angles and velocities that are exhibited during the completion of functional tasks. As Section A of the thesis consistently identified that muscular strength is influenced by knee joint angles and velocities, these parameters should inform further screening methods. Knee joint angles and velocities can be defined during biomechanical assessments of tasks associated with lower limb injuries, and may enable increased specificity of strength profiling for the thigh musculature. Specifically, quantification of knee joint angles and velocities may inform methods to determine thigh musculature strength values during the completion of functional tasks. Biomechanical assessments of the knee joint during functional tasks may also identify differences between female soccer playing age, particularly when youths are predisposed to an increased risk of ACL injury (Renstrom et al. 2008, Hägglund and Waldén, 2016). Therefore, section B of the thesis assessed knee biomechanics between senior and youth female soccer players during functional tasks, where these movements were also used to inform additional methods for quantifying thigh musculature strength.

A limited number significant differences in sagittal and frontal plane knee biomechanics were identified between senior and youth female soccer players during hopping tasks. These findings were also consistent at initial ground contact, and during the loading and propulsive phases of hopping manoeuvres that are associated with injury risk (Quatman, Quatman-Yates and Hewett, 2010; Hewett and Myer, 2011; Benche et al. 2012; Norcross et al. 2013). Although hopping manoeuvres have previously identified significant differences between injured and non-injured participants (Ortiz et al. 2011), the kinematic and kinetic variables derived from these tasks may not sufficiently determine differences in knee biomechanics across healthy female soccer playing ages. However, when considering that youth female soccer players possessed significantly lower AST strength values when compared to senior aged players, youths may also demonstrate strength discrepancies during the completion of functional tasks associated with injury.

The sagittal plane knee joint angles and velocities exhibited during hopping tasks were similar to those observed during isokinetic dynamometry, and were used to inform additional screening methods within section B of the thesis. Specifically, this entailed quantifying thigh musculature strength during hopping tasks as a function of knee joint angle and velocity, relative to female soccer playing age. Following additional isokinetic strength assessments in accordance with the procedures defined in section A, it was identified that knee joint angle and velocity were significant predictors of thigh musculature strength in both senior and youth female soccer players. These regression analyses validated algorithms to predict thigh musculature strength at precise knee joint angles and velocities that may be used to quantify strength during functional tasks. Further biomechanical assessments of hopping tasks and the associated knee joint angles and velocities were inputted into the predictive equations to subsequently compare between senior and youth female soccer players. No significant differences in peak predicted thigh musculature strength values were identified between female soccer playing ages. However, significantly higher strength values were exhibited across all other defined events in senior female soccer players when compared to youths, irrespective of hopping manoeuvre. These findings may be important as youth players demonstrated significantly lower strength values during periods where injury risk is reportedly increased, such as initial contact, loading and propulsive phases of functional tasks (Quatman, Quatman-Yates and Hewett, 2010; Hewett and Myer, 2011; Benche et al. 2012; Norcross et al. 2013). As such, these approaches are able to determine strength differences between female soccer playing ages during phases of movement associated with lower limb injury, and provide further insight into possible factors that may influence increased injury risk in youth players.

Determining predictive equations for thigh musculature strength and biomechanically assessing movements can identify strength at precise knee joint angles and velocities with enhanced functional relevance. These approaches were also able to identify if the thigh musculature are sufficiently developed to dissipate the moments placed upon the knee joint during the completion of functional tasks. Although enlarged internal KE moments have been associated with increased risk of knee ligament injury (Shimokochi et al. 2009; Hewett et al. 2010; Leppänen et al. 2017), it was unknown whether these demands are disproportionate to the thigh musculature strength capacities. The present data observed that the eccKF and conKE were significantly higher than KE moments for loading and propulsive phases of hopping tasks for both female playing ages. However, it was also identified that the KE moments were significantly higher at initial ground contact when compared to the eccKF for both senior and youth female soccer players. In turn, these significant differences coincided with the point when risk of knee ligament injury is possibly highest (Boden and Dean, 2000; Hewett and Myer, 2011; Benche et al. 2012; Norcross et al. 2013), thus the eccKF have increased demands to counter KE moments. Although the knee joint moments were not significantly different between female soccer playing ages, youth female soccer players possessed significantly lower thigh musculature strength values during hopping tasks. Therefore, it can be suggested that youth female soccer players may be at an increased injury risk due to increased relative demands of the thigh musculature to maintain postural control and dissipate large impact forces. These considerations may identify further biomechanical discrepancies between senior and youth female soccer players that may have potential implications for injury risk.

Thigh musculature strength is commonly determined at slow testing velocities that quantifies PT and DCR using isokinetic dynamometry. Whilst these approaches are indicative of absolute strength and their associated strength ratios of soccer players, such methods lack functional relevance to movement. As such, the thesis has identified isokinetic strength characteristics of the thigh musculature at increasingly relevant knee joint angles and velocities in soccer players that better resemble functional movements. Nevertheless, these procedures are unable to define strength at particular knee joint angles and velocities during the completion of functional tasks associated with injury. Consequently, this thesis has developed a new concept for determining thigh musculature strength. By biomechanically analysing movements specific to the demands of soccer that are also associated with mechanisms of lower limb injury, thigh musculature strength can be determined during these tasks at specific phases where the athlete performs. Through the development of predictive equations, kinematic data of the knee joint derived from biomechanical assessments can quantify thigh musculature strength at specific phases of movement where injury risk may increase. These approaches are also able to identify if the thigh musculature are sufficiently conditioned to dissipate

11.3 Future Recommendations and Limitations

There are a number of limitations associated with the studies comprised within the thesis, with implications for future research. The procedures and metrics associated with isokinetic dynamometry in section A of the thesis considers strength metrics that better represent the aetiological factors of thigh musculature and knee ligament injuries. However, it was not possible to obtain data at extreme joint angles and velocities where injury risk may further increase. It was also not possible to capture data at individual joint angles due to the sampling frequency of the dynamometer used. Irrespective of the aforementioned limitations, isokinetic dynamometry and muscular strength testing is commonly performed in soccer. It is therefore important for sports scientists and fitness coaches alike to identify the limitations of equipment, but as identified in the current thesis, practitioners should attempt to develop methods to better utilise equipment to further inform practice.

Section A of the thesis focused on methods to enhance screening and analytical methods of isokinetic strength assessments of the eccKF and conKE musculature. As muscular strength deficits and imbalances have been associated with thigh musculature and knee ligament injuries in soccer players (Croisier et al. 2008; Lee et al. 2017), muscular strength has therefore been identified to be a modifiable risk factor for such injuries. Prospective studies have previously conducted isokinetic strength assessments with specific focus of KF injuries in senior aged male soccer players (Croisier et al. 2008; Van Dyk et al. 2016, 2017; Lee et al. 2017; Bakken et al. 2018), although similar studies have yet to be conducted using the approaches defined within the thesis and in relation to knee ligament injuries. No prospective study has also been conducted in youth males or female soccer players in relation to isokinetic strength assessments, thus future studies could utilise the defined procedures in Section A of the thesis to establish an association with thigh musculature and knee ligament injuries.

Although the approaches in Section A have also considered injury status, limb dominance, playing age and gender of the soccer player, other factors also appear to influence injury risk. For instance, acute and cumulative periods of soccer-specific activity are associated with increased risk of KF injury (Hawkins et al. 2001; Ekstrand et al. 2011). This has resulted in significant reductions in KF PT during simulations of soccer match-play and fixture congestion (Greig, 2008; Small et al. 2010; Page et al. 2017). The procedures defined in Section A of the thesis could also assess the strength responses of the KF in relation to soccer-specific exercise, relative to age, limb dominance and gender of the soccer player.

The procedures and metrics defined in Section A of the thesis identified significant differences between senior and youth soccer players, relative to gender. As such, these findings identify additional strength training needs of youth players who begin to participate against senior aged players that may be influenced by, but not limited to adolescent growth. As the effects of adolescent growth were not determined in either study 3 or 4 of the thesis, this may be considered as a potential limitation. The current procedures could therefore be determined in future research in younger aged players to determine the effects of adolescent growth where injury risk begins to increase. This may also be considered in future studies that could assess knee biomechanics of youth female soccer players where risk of knee ligament injuries also begin to increase.

In relation to section B of the thesis, the studies comprised within this section also have limitations. For instance, as it has been suggested that ACL injury risk is highest during and following 0.1 seconds following ground contact of functional tasks, the sampling frequency of 120Hz provides only 5 frames of footage to analyse during this period. As such, the camera sampling frequency used in these studies may be a limitation, thus further research using higher sampling frequencies may be required in these populations to more appropriately identify injury risk. As injury risk may also be increased during movements with higher knee joint angular velocities, the use of hopping tasks could also be considered a limitation. Therefore, future research investigating the biomechanical differences between senior and youth female soccer players may wish to utilise increased camera sampling frequencies to better determine knee ligament injury risk during periods of high-risk period of movement.

With specific reference to study 5, future research could also assess the influence of hip and trunk biomechanics between senior and youth female soccer players in relation to knee ligament injury risk (Hewett et al. 2010; Hewett and Myer, 2011; Frank et al. 2013). A potential limitation of this study was that unanticipated cutting manoeuvres were not explored, particularly when these tasks are suggested to possess enhanced sport specificity and better determine injury risk (Ford et al. 2005; Meinerz et al. 2015; Yom et al. 2018). In an attempt to better determine whether the knee kinematics and kinetics derived from hopping tasks can identify differences between female soccer playing ages, unanticipated trials should also be assessed.

Study 6 focused on the development of age specific algorithms for predicting thigh musculature strength during hopping tasks, and to enable comparisons between female soccer players. It must be acknowledged that the algorithms developed in this study were specific to the movement, contraction modes and populations used. These measures therefore cannot be currently generalised beyond these defined procedures. Moreover, as this study did not determine eccentric KE strength, it was not possible to predict strength values of these musculature during loading phases of hopping manoeuvres. As eccentric KE strength is required to sufficiently dissipate impact forces during the completion of functional tasks (Podraza and White, 2010; Norcross et al. 2010), defining these strength values may better identify differences between female soccer playing ages. Subsequently, it was also not possible to identify if the strength capacity of the eccentric KE were proportionate to the KE exhibited during the completion of hopping manoeuvres. As a consequence, future studies should also assess and determine eccentric KE in accordance with the procedures outlined in Section A of the thesis.

This thesis has provided further methodological and analytical approaches for determining thigh musculature strength associated with isokinetic dynamometry, relative to injury status, limb dominance, playing age and gender of elite soccer players. Muscular strength has also been associated with thigh musculature and knee ligament injuries in sports such as basketball, rugby, netball, football and handball (Hootman, Dick and Agel, 2007; Renstrom et al. 2008; Freckleton and Pizzari, 2013; Opar et al. 2015). The present procedures and analytical approaches may also be used within these aforementioned sports to characterise thigh musculature strength. Moreover, the same principles used to inform the defined approaches in this thesis may also be applied to various joints of the body to further enhance the efficacy of isokinetic dynamometry to profile muscular strength.

11.4 Conclusion

The thesis has identified that isokinetic eccKF and conKE strength are influenced by knee joint angle and velocity across elite soccer players, relative to injury status, limb dominance, playing age and gender. The procedures and analytical approaches consequently did not identify a conKE strength dominance across these cohorts of players that is commonly cited as a risk factor for KF and ACL injuries (Hewett et al. 2007; Croisier et al. 2008; Lee et al. 2017). Whilst the PT and DCR metrics appear appropriate for distinguishing between injured players and those with dissimilar weekly training demands, these metrics are not able to identify discrepancies between soccer players with increasingly subtle differences. The AST strength metrics defined across testing velocities consistently identified significant differences between all cohorts of players, including players with similar weekly training demands and smaller strength differences. Therefore, defining AST strength across a variety of angular velocities are advocated by this thesis, and can highlight additional strength training needs of soccer players that may have implications for potential injury risk and exercise prescription.

Although AST strength metrics possess enhanced functional relevance when compared to previous methods that determine thigh musculature strength, these procedures are unable to identify strength at particular knee joint angles and velocities exhibited during the completion of functional tasks. To quantify thigh musculature strength during functional tasks, biomechanical assessments of the knee joint are required. The knee kinematics exhibited during the completion of functional tasks identified the joint angles and velocities that were subsequently used to express thigh musculature strength between female soccer playing ages. These predictive equations identified significantly higher values in senior aged female players across all defined phases of hopping tasks when compared to youths. Further analyses also revealed that the predicted eccKF strength values during initial ground contact were significantly lower than KE moments, thereby placing an increased demand of these musculature to counteract large forces where injury risk is increased (Li et al. 1999; MacWilliams et al. 1999; Chmielewski et al. 2002; Hewett and Myer, 2011; Benche et al. 2012; Norcross et al. 2013). As the sagittal and frontal plane knee biomechanics were not significantly different between female soccer playing ages, these predictive equations identify further differences that may influence increased injury risk in youth players (LeGall et al. 2008; Hartmut et al. 2008; Renstrom et al. 2008; Hägglund and Waldén, 2015).

The PT and DCR metrics determine isokinetic strength of the thigh musculature at slow testing velocities in soccer players, and lack functional relevance to movements associated with injury risk. Whilst angle and velocity specific measures of thigh musculature strength have increased functional relevance to those observed in movements associated with injury risk, the defined procedures are unable to quantify strength during the completion of these tasks. Determining angle and velocity specific strength of the thigh musculature from isokinetic dynamometry can be used to generate predictive equations, specific to female soccer playing age. In turn, these algorithms can be used to quantify thigh musculature strength following biomechanical assessments of the knee joint during functional tasks. The body of work comprised within the thesis has developed further methods for assessing and determining thigh musculature strength by identifying additional training needs of soccer players, and additional discrepancies that may influence potential injury risk.

CHAPTER 12

References

AAGAARD, P., SIMONSEN, E.B., MAGNUSSON, S.P., LARSSON, B., and DYHRE-POULSEN, P., 1998. A New Concept For Isokinetic Hamstring: Quadriceps Muscle Strength Ratio. *The American Journal of Sports Medicine*. 26 (2), pp. 231–237.

AAGAARD, P., SIMONSEN, E.B., TROLLE, M., BANGSBO, J., and KLAUSEN, K., 1995. Isokinetic hamstring/quadriceps strength ratio: influence from joint angular velocity, gravity correction and contraction mode. *Acta Physiologica Scandinavica*. 154 (4), pp. 421–427.

ABBASSI, V., 1998. Growth and normal puberty. *Pediatrics*. 102, pp. 507–11.

ABERNETHY, P., WILSON, G., and LOGAN, P., 1995. Strength and power assessment. Issues, controversies and challenges. *Sports Medicine*. 19 (6), pp. 401–17.

AL ATTAR, W.S.A., SOOMRO, N., SINCLAIR, P.J., PAPPAS, E., and SANDERS, R.H., 2017. Effect of Injury Prevention Programs that Include the Nordic Hamstring Exercise on Hamstring Injury Rates in Soccer Players: A Systematic Review and Meta-Analysis. *Sports Medicine*. 47(5), pp. 907-916

ASKLING, C., KARLSSON, J., and THORSTENSSON, A., 2003. Hamstring injury occurrence in elite soccer players after preseason strength training with eccentric overload. *Scandinavian Journal of Medicine and Science in Sports*. 13 (4), pp. 244–250.

AUGUSTSSON, S. and AGEBERG, E., 2017. Weaker lower extremity muscle strength predicts traumatic knee injury in youth female but not male athletes. *BMJ Open Sport & Exercise Medicine*. 3 (1), p. e000222.

BAHR, R. and HOLME, I., 2003. Risk factors for sports injuries-a methodological approach. *British Journal of Sports Medicine*. 37 (5), pp. 384–92.

BAHR, R., 2016. Why screening tests to predict injury do not work-and probably never will. A critical review. *British Journal of Sports Medicine*. 50 (13), pp.776-780.

BAHR, R., CLARSEN, B., and EKSTRAND, J., 2017. Why we should focus on the burden of injuries and illnesses, not just their incidence. *British Journal of Sports Medicine*. p. bjsports-2017-098160.

BAKKEN, A., TARGETT, S., BERE, T., EIRALE, C., FAROOQ, A., MOSLER, A.B., TOL, J.L., WHITELEY, R., KHAN, K.M., and BAHR, R., 2018. Muscle Strength Is a Poor Screening Test for Predicting Lower Extremity Injuries in Professional Male Soccer Players: A 2-Year Prospective Cohort Study. *The American Journal of Sports Medicine*. p. 036354651875602.

BARAK, Y., AYALON, M., and DVIR, Z., 2004. Transferability of strength gains from limited to full range of motion. *Medicine and Science in Sports and Exercise*. 36 (8), pp. 1413–1420.

BENNELL, K., WAJSWELNER, H., LEW, P., SCHALL-RIAUCOUR, A., LESLIE, S., PLANT, D., and CIRONE, J., 1998. Isokinetic strength testing does not predict hamstring injury in Australian Rules footballers. *British Journal of Sports Medicine*. 32 (4), pp. 309–314.

BESIER, T.F., LLOYD, D.G., COCHRANE, J.L., and ACKLAND, T.R., 2001. External loading of the knee joint during running and cutting maneuvers. *Medicine and Science in Sports and Exercise*. pp. 1168–1175.

BLOOMFIELD, J., POLMAN, R., and O'DONOGHUE, P., 2007. Physical demands of different positions in FA Premier League soccer. *Journal of Sports Science and Medicine*. 6 (1), pp. 63–70.

BODEN, B.P., DEAN, G.S., FEAGIN, J.A., and GARRETT, W.E., 2000. Mechanisms of anterior cruciate ligament injury. *Orthopedics*. 23 (6), pp. 573–578.

BODEN, B.P., TORG, J.S., KNOWLES, S.B., and HEWETT, T.E., 2009. Video analysis of anterior cruciate ligament injury: abnormalities in hip and ankle kinematics. *The American Journal of Sports Medicine*. 37 (2), pp. 252–9.

BONETTI, L.V., FLORIANO, L.L., DOS SANTOS, T.A., SEGALLA, F.M., BIONDO, S., and TADIELLO, G.S., 2017. Isokinetic performance of knee extensors and flexors in adolescent male soccer athletes. *Sport Sciences for Health*. 13 (2), pp. 315–321.

BROPHY, R., SILVERS, H.J., GONZALES, T., and MANDELBAUM, B.R., 2010. Gender influences: The role of leg dominance in ACL injury among soccer players. *British Journal of Sports Medicine*. 44 (10), pp. 694–697.

BROPHY, R.H., SCHMITZ, L., WRIGHT, R.W., DUNN, W.R., PARKER, R.D., ANDRISH, J.T., MCCARTY, E.C., and SPINDLER, K.P., 2012. Return to play and future ACL injury risk after ACL reconstruction in soccer athletes from the multicenter orthopaedic outcomes network (MOON) group. *American Journal of Sports Medicine*. 40 (11), pp. 2517–2522.

BROPHY, R.H., STEPAN, J.G., SILVERS, H.J., and MANDELBAUM, B.R., 2015. Defending Puts the Anterior Cruciate Ligament at Risk During Soccer: A Gender-Based Analysis. *Sports Health*. 7 (3), pp. 244–249.

CAMPENELLA, B., MATTACOLA, C.G., and KIMURA, I.F., 2000. Effect of visual feedback and verbal encouragement on concentric quadriceps and hamstrings peak torque of males and females. *Isokinetics and Exercise Science*. 8, pp. 1–6.

CHMIELEWSKI, T.L., RUDOLPH, K.S., and SNYDER-MACKLER, L., 2002. Development of dynamic knee stability after acute ACL injury. *Journal of Electromyography and Kinesiology*. 12 (4), pp. 267–274.

CHUMANOV, E.S., SCHACHE, A.G., HEIDERSCHEIT, B.C., and THELEN, D.G., 2012. Hamstrings are most susceptible to injury during the late swing phase of sprinting. *British Journal of Sports Medicine*. 46 (2), p. 90.

COHEN, D.D., ZHAO, B., OKWERA, B., MATTHEWS, M.J., and DELEXTRAT, A., 2015. Angle-specific eccentric hamstring fatigue after simulated soccer. *International Journal of Sports Physiology and Performance*. 10 (3), pp. 325–331.

CROISIER, J.-L., FORTHOMME, B., NAMUROIS, M.-H., VANDERTHOMMEN, M., and CRIELAARD, J.-M., 2002. Hamstring Muscle Strain Recurrence and Strength Performance Disorders. *The American Journal of Sports Medicine*. 30 (2), pp. 199–203.

CROISIER, J.L., GANTEAUME, S., BINET, J., GENTY, M., and FERRET, J.M., 2008. Strength imbalances and prevention of hamstring injury in professional soccer players: A prospective study. *American Journal of Sports Medicine*. 36 (8), pp. 1469–1475.

CZAPLICKI, A., JAROCKA, M., and WALAWSKI, J., 2015. Isokinetic identification of knee joint torques before and after anterior cruciate ligament reconstruction. *PLoS ONE*. 10 (12).

DANESHJOO, A., MOKHTAR, A.H., RAHNAMA, N., and YUSOF, A., 2012. The Effects of Injury Preventive Warm-Up Programs on Knee Strength Ratio in Young Male Professional Soccer Players. *PLoS ONE*. 7 (12).

DAUTY, M., MENU, P., and FOUASSON-CHAILLOUX, A., 2018. Cutoffs of isokinetic strength ratio and hamstring strain prediction in professional soccer players. *Scandinavian Journal of Medicine and Science in Sports*. 28 (1), pp. 276–281.

DE STE CROIX, M.B.A., ARMSTRONG, N., and WELSMAN, J.R., 1999. Concentric isokinetic leg strength in pre-teen, teenage and adult males and females. *Biology of Sport*. 16 (2), pp. 75–86.

DE STE CROIX, M.B.A., ARMSTRONG, N., WELSMAN, J.R., and SHARPE, P., 2002. Longitudinal changes in isokinetic leg strength in 10-14-year-olds. *Annals of Human Biology*. 29 (1), pp. 50–62.

DE STE CROIX, M.B.A., ELNAGAR, Y.O., IGA, J., AYALA, F. and JAMES, D., 2017. The impact of joint angle and movement velocity on sex differences in the functional hamstring/quadriceps ratio. *The Knee*. *24*(4), pp.745-750.

DE VILLARREAL, E.S.S., REQUENA, B., NEWTON, R.U., SAEZ-SAEZ DE VILLARREAL, E., REQUENA, B., NEWTON, R.U., DE VILLARREAL, E.S.S., REQUENA, B., and NEWTON, R.U., 2010. Does plyometric training improve strength performance? A meta-analysis. *Journal of Science and Medicine in Sport*. 13 (5), pp. 513–522.

DEVAN, M.R., PESCATELLO, L.S., FAGHRI, P., and ANDERSON, J., 2004. A prospective study of overuse knee injuries among female athletes with muscle imbalances and structural abnormalities. *Journal of Athletic Training*. 39 (3), pp. 263–267.

DOORENBOSCH, C.A.M. and HARLAAR, J., 2003. A clinically applicable EMG-force model to quantify active stabilization of the knee after a lesion of the anterior cruciate ligament. *Clinical Biomechanics*. 18 (2), pp. 142–149.

DOWLING, A. V., FAVRE, J., and ANDRIACCHI, T.P., 2012. Inertial sensor-based feedback can reduce key risk metrics for anterior cruciate ligament injury during jump landings. *American Journal of Sports Medicine*. 40 (5), pp. 1075–1083.

DVIR, Z., 2014. Relevant, less relevant and irrelevant isokinetic strength test parameters: Some critical comments. *Movement & Sport Sciences - Science & Motricité*. (85), pp. 15–21.

EKSTRAND, J., HÄGGLUND, M., and WALDÉN, M., 2011. Injury incidence and injury patterns in professional football - the UEFA injury study Injury incidence and injury patterns in professional football – the UEFA Injury Study. *American Journal of Sports Medicine*. 45 (7), pp. 533–538.

EKSTRAND, J., HÄGGLUND, M., KRISTENSON, K., MAGNUSSON, H., and WALDÉN, M., 2013. Fewer ligament injuries but no preventive effect on muscle injuries and severe injuries: An 11-year follow-up of the UEFA Champions League injury study. *British Journal of Sports Medicine*. 47 (12), pp. 732–737.

EVANGELIDIS, P.E., PAIN, M.T.G., and FOLLAND, J., 2015. Angle-specific hamstring-to-quadriceps ratio: A comparison of football players and recreationally active males. *Journal of Sports Sciences*. 33 (3), pp. 309–319.

FAUDE, O., JUNGE, A., KINDERMANN, W., and DVORAK, J., 2005. Injuries in Female Soccer Players. *The American Journal of Sports Medicine*. 33 (11), pp. 1694–1700.

FERBER, R., DAVIS, I.M.C., and WILLIAMS, D.S., 2003. Gender differences in lower extremity mechanics during running. *Clinical Biomechanics*. 18 (4), pp. 350–357.

FINCH, C., 2006. *Journal of Science and Medicine in Sport*.

FORBES, H., BULLERS, A., LOVELL, A., MCNAUGHTON, L.R., POLMAN, R.C., and SIEGLER, J.C., 2009. Relative torque profiles of elite male youth footballers: Effects of age and pubertal development. *International Journal of Sports Medicine*. 30 (8), pp. 592–597.

FORBES, H., SUTCLIFFE, S., LOVELL, A., MCNAUGHTON, L.R., and SIEGLER, J.C., 2009. Isokinetic thigh muscle ratios in youth football: Effect of age and dominance. *International Journal of Sports Medicine*. 30 (8), pp. 602–606.

FORD, K.R., DICESARE, C.A., MYER, G.D., and HEWETT, T.E., 2015. Real-Time Biofeedback to Target Risk of Anterior Cruciate Ligament Injury: A Technical Report for Injury Prevention and Rehabilitation. *Journal of Sport Rehabilitation*.

FORD, K.R., MYER, G.D., and HEWETT, T.E., 2003. Valgus knee motion during landing in high school female and male basketball players. *Medicine and Science in Sports and Exercise*. 35 (10), pp. 1745–1750.

FORD, K.R., MYER, G.D., TOMS, H.E., and HEWETT, T.E., 2005. Gender differences in the kinematics of unanticipated cutting in young athletes. *Medicine and Science in Sports and Exercise*. 37 (1), pp. 124–129.

FORD, K.R., SHAPIRO, R., MYER, G.D., VAN DEN BOGERT, A.J., and HEWETT, T.E., 2010. Longitudinal sex differences during landing in knee abduction in young athletes. *Medicine and Science in Sports and Exercise*. 42 (10), pp. 1923–1931.

FOUSEKIS, K., TSEPIS, E., and VAGENAS, G., 2010. Lower limb strength in professional soccer players: Profile, asymmetry, and training age. *Journal of Sports Science and Medicine*. 9 (3), pp. 364–373.

FOUSEKIS, K., TSEPIS, E., POULMEDIS, P., ATHANASOPOULOS, S., and VAGENAS, G., 2011. Intrinsic risk factors of non-contact quadriceps and hamstring strains in soccer: A prospective study of 100 professional players. *British Journal of Sports Medicine*. 45 (9), pp. 709–714.

FOX, A.S., BONACCI, J., MCLEAN, S.G., and SAUNDERS, N., 2017. Efficacy of ACL injury risk screening methods in identifying high-risk landing patterns during a sport-specific task. *Scandinavian Journal of Medicine and Science in Sports*. 27 (5), pp. 525–534.

FRANK, B., BELL, D.R., NORCROSS, M.F., BLACKBURN, J.T., GOERGER, B.M., and PADUA, D.A., 2013. Trunk and hip biomechanics influence anterior cruciate loading mechanisms in physically active participants. *American Journal of Sports Medicine*. 41 (11), pp. 2676–2683.

FRECKLETON, G. and PIZZARI, T., 2013. Risk factors for hamstring muscle strain injury in sport: a systematic review and meta-analysis. *British Journal of Sports Medicine*. 47 (6), pp. 351–358.

FULTON, J., WRIGHT, K., KELLY, M., ZEBROSKY, B., ZANIS, M., DRVOL, C., and BUTLER, R., 2014. Injury risk is altered by previous injury: a systematic review of the literature and presentation of causative neuromuscular factors. *International Journal of Sports Physical Therapy*. 9 (5), pp. 583–595.

GILCHRIST, J., MANDELBAUM, B.R., MELANCON, H., RYAN, G.W., SILVERS, H.J., GRIFFIN, L.Y., WATANABE, D.S., DICK, R.W., and DVORAK, J., 2008. A randomized controlled trial to prevent noncontact anterior cruciate ligament injury in female collegiate soccer players. *American Journal of Sports Medicine*. 36 (8), pp. 1476–1483.

GRANADOS, A., GEBREMARIAM, A., and LEE, J.M., 2015. Relationship between timing of peak height velocity and pubertal staging in boys and girls. *JCRPE Journal of Clinical Research in Pediatric Endocrinology*. 7 (3), pp. 235–237.

GREIG, M., 2008. The influence of soccer-specific fatigue on peak isokinetic torque production of the knee flexors and extensors. *American Journal of Sports Medicine*. 36 (7), pp. 1403–1409.

GREIG, M. and SIEGLER, J.C., 2009. Soccer-specific fatigue and eccentric hamstrings muscle strength. *Journal of Athletic Training*. 44 (2), pp. 180–184.

GREIG, M., 2009. The influence of soccer-specific activity on the kinematics of an agility sprint. *European Journal of Sport Science*. 9 (1), pp. 23–33.

GRINDEM, H., SNYDER-MACKLER, L., MOKSNES, H., ENGEBRETSEN, L., and RISBERG, M.A., 2016. Simple decision rules can reduce reinjury risk by 84% after ACL reconstruction: The Delaware-Oslo ACL cohort study. *British Journal of Sports Medicine*. 50 (13), pp. 804–808.

GROSS, M.T., MCGRAIN, P., DEMILIO, N., and PLYLER, L., 1989. Relationship between multiple predictor variables and normal knee torque production. *Physical Therapy*. 69 (1), pp. 54–62.

GUEX, K. and MILLET, G.P., 2013. Conceptual framework for strengthening exercises to prevent hamstring strains. *Sports Medicine*.

GÜR, H., AKOVA, B., PÜNDÜK, Z., and KÜÇÜKOĞLU, S., 1999. Effects of age on the reciprocal peak torque ratios during knee muscle contractions in elite soccer players. *Scandinavian Journal of Medicine & Science in Sports*. 9 (2), pp. 81–87.

HÄGGLUND, M. and WALDÉN, M., 2016. Risk factors for acute knee injury in female youth football. *Knee Surgery, Sports Traumatology, Arthroscopy*. 24 (3), pp. 737–746.

HÄGGLUND, M., WALDÉN, M., and EKSTRAND, J., 2013. Risk factors for lower extremity muscle injury in professional soccer: the UEFA Injury Study. *The American journal of sports medicine*. 41 (2), pp. 327–35.

HÄGGLUND, M., WALDÉN, M., BAHR, R., and EKSTRAND, J., 2005. Methods for epidemiological study of injuries to professional football players: Developing the UEFA model. *British Journal of Sports Medicine*. (6), pp. 340-346.

HAMILTON, R.T., SHULTZ, S.J., SCHMITZ, R.J., and PERRIN, D.H., 2008. Triple-hop distance as a valid predictor of lower limb strength and power. *Journal of Athletic Training*. 43 (2), pp. 144–151.

HARRISON, A.D., FORD, K.R., MYER, G.D., and HEWETT, T.E., 2011. Sex differences in force attenuation: A clinical assessment of single-leg hop performance on a portable force plate. *British Journal of Sports Medicine*. 45 (3), pp. 198–202.

HARTMUT, G., BECKER, A., WALTHER, M., and HESS, H., 2010. Injuries in Women,s soccer: A 1-year all players prospective field study of the Women's bundesliga (German Premier League). *Clinical Journal of Sport Medicine*. 20 (4), pp. 264–271.

HAVENS, K.L. and SIGWARD, S.M., 2015. Cutting mechanics: Relation to performance and anterior cruciate ligament injury risk. *Medicine and Science in Sports and Exercise*. 47 (4), pp. 818–824.

HAWKINS, R.D. and FULLER, C.W., 1999. A prospective epidemiological study of injuries in four English professional football clubs. *British Journal of Sports Medicine*. 33 (3), pp. 196–203.

HEISER, T.M., WEBER, J., SULLIVAN, G., CLARE, P., and JACOBS, R.R., 1984. Prophylaxis and management of hamstring muscle injuries in intercollegiate football players. *The American Journal of Sports Medicine*. 12 (5), pp. 368–370.

HEWETT, T.E. and MYER, G.D., 2011. The mechanistic connection between the trunk, hip, knee, and anterior cruciate ligament injury. *Exercise and Sport Sciences Reviews*. 39(4), pp. 161-166

HEWETT, T.E., FORD, K.R., HOOGENBOOM, B.J., and MYER, G.D., 2010. Understanding and preventing acl injuries: current biomechanical and epidemiologic considerations - update 2010. *North American Journal of Sports Physical Therapy : NAJSPT*. 5 (4), pp. 234–251.

HEWETT, T.E., MYER, G.D., and FORD, K.R., 2004. Decrease in neuromuscular control about the knee with maturation in female athletes. *Journal of Bone and Joint Surgery - Series A*. 86 (8), pp. 1601–1608.

HEWETT, T.E., MYER, G.D., and ZAZULAK, B.T., 2008. Hamstrings to quadriceps peak torque ratios diverge between sexes with increasing isokinetic angular velocity. *Journal of Science and Medicine in Sport*. 11 (5), pp. 452–459.

HEWETT, T.E., MYER, G.D., FORD, K.R., and SLAUTERBECK, J.R., 2006. Preparticipation physical examination using a box drop vertical jump test in young athletes: The effects of puberty and sex. *Clinical Journal of Sport Medicine*. 16 (4), pp. 298–304.

HEWETT, T.E., MYER, G.D., FORD, K.R., HEIDT, R.S., COLOSIMO, A.J., MCLEAN, S.G., VAN DEN BOGERT, A.J., PATERNO, M. V., and SUCCOP, P., 2005. Biomechanical measures of neuromuscular control and valgus loading of the knee predict anterior cruciate ligament injury risk in female athletes: A prospective study. *American Journal of Sports Medicine*. 33 (4), pp. 492–501.

HEWETT, T.E., MYER, G.D., KIEFER, A.W., and FORD, K.R., 2015. Longitudinal Increases in Knee Abduction Moments in Females during Adolescent Growth. *Medicine and Science in Sports and Exercise*. 47 (12), pp. 2579–2585.

HIGASHIHARA, A., NAGANO, Y., ONO, T., and FUKUBAYASHI, T., 2015. Differences in activation properties of the hamstring muscles during overground sprinting. *Gait and Posture*. 42 (3), pp. 360–364.

HOOTMAN, J.M., DICK, R., and AGEL, J., 2007. Epidemiology of collegiate injuries for 15 sports: Summary and recommendations for injury prevention initiatives. *Journal of Athletic Training*. 42(2), pp. 311-319

HSIAO, S.-F., CHOU, P.-H., HSU, H.-C., and LUE, Y.-J., 2014. Changes of muscle mechanics associated with anterior cruciate ligament deficiency and reconstruction. *Journal of Strength and Conditioning Research / National Strength & Conditioning Association*. 28 (2), pp. 390–400.

HUGHES, G. and WATKINS, J., 2006. A risk-factor model for anterior cruciate ligament injury. *Sports Medicine*. 36 (5), pp. 411–428.

IGA, J., GEORGE, K., LEES, A., and REILLY, T., 2006. Reliability of assessing indices of isokinetic leg strength in pubertal soccer players. *Pediatric Exercise Science*. 18 (4), p. 436–445 10p.

IGA, J., GEORGE, K., LEES, A., and REILLY, T., 2009. Cross-Sectional investigation of indices of isokinetic leg strength in youth soccer players and untrained individuals. *Scandinavian Journal of Medicine and Science in Sports*. 19 (5), pp. 714–719.

IMPELLIZZERI, F.M., BIZZINI, M., RAMPININI, E., CEREDA, F., and MAFFIULETTI, N.A., 2008. Reliability of isokinetic strength imbalance ratios measured using the Cybex NORM dynamometer. *Clinical Physiology and Functional Imaging*. 28 (2), pp. 113–119.

IMWALLE, L.E., MYER, G.D., FORD, K.R., and HEWETT, T.E., 2009. Relationship Between Hip and Knee Kinematics in Athletic Women During Cutting Maneuvers: A Possible Link to Noncontact Anterior Cruciate Ligament Injury and Prevention. *Journal of Strength and Conditioning Research*. 23 (8), pp. 2223–2230.

JENKINS, N.D.M., HAWKEY, M.J., COSTA, P.B., FIDDLER, R.E., THOMPSON, B.J., RYAN, E.D., SMITH, D., SOBOLEWSKI, E.J., CONCHOLA, E.C., AKEHI, K., and CRAMER, J.T., 2013. Functional hamstrings: Quadriceps ratios in elite women's soccer players. *Journal of Sports Sciences*. 31 (6), pp. 612–617.

JINDRICH, D.L., BESIER, T.F., and LLOYD, D.G., 2006. A hypothesis for the function of braking forces during running turns. *Journal of Biomechanics*. 39 (9), pp. 1611–1620.

KAWAMORI, N. and HAFF, G.G., 2004. The optimal training load for the development of muscular power. *Journal of Strength and Conditioning Research*. 18(3), pp. 675-84.

KAWAMORI, N. and NEWTON, R.U., 2006. Velocity specificity of resistance training: Actual movement velocity versus intention to move explosively. *Strength and Conditioning Journal*. 28 (2), pp. 86-91.

KELLIS, E., ARABATZI, F., and PAPADOPOULOS, C., 2003. Muscle co-activation around the knee in drop jumping using the co-contraction index. *Journal of Electromyography and Kinesiology*. 13 (3), pp. 229–238.

KELLIS, E., KELLIS, S., GERODIMOS, V., and MANOU, V., 1999. Reliability of isokinetic concentric and eccentric strength in circumpubertal soccer players. *Pediatric Exercise Science*. 11 (3), pp. 218–228.

KERNOZEK, T.W., TORRY, M.R., VAN HOOF, H., COWLEY, H., and TANNER, S., 2005. Gender differences in frontal and sagittal plane biomechanics during drop landings. *Medicine and Science in Sports and Exercise*. 37 (6), pp. 1003–1012.

KIAPOUR, A.M. and MURRAY, M.M., 2014. Basic science of anterior cruciate ligament injury and repair. *Bone & Joint Research*. 3 (2), pp. 20–31.

KIEFER, A.W., KUSHNER, A.M., GROENE, J., WILLIAMS, C., RILEY, M.A., and MYER, G.D., 2014. A commentary on real-time biofeedback to augment neuromuscular training for ACL injury prevention in adolescent athletes. *Journal of Sports Science and Medicine*. 14 (1), pp. 1–8.

KIM, D. and HONG, J., 2011. Hamstring to quadriceps strength ratio and noncontact leg injuries: A prospective study during one season. *Isokinetics and Exercise Science*. 19 (1), pp. 1–6.

KIVI, D.M.R., MARAJ, B.K. V, and GERVAIS, P., 2002. A kinematic analysis of high-speed treadmill sprinting over a range of velocities. *Medicine and science in sports and exercise*. 34 (4), pp. 662–666.

KOMI, P.V., ISHIKAWA, M. AND LINNAMO, V., 2011. Identification of Stretch-Shortening Cycles in different sports. In *ISBS-Conference Proceedings Archive* (Vol. 1, No. 1).

KRISTIANSLUND, E. and KROSSHAUG, T., 2011. Sidestep cutting technique affects knee valgus loading. *British Journal of Sports Medicine*. 45 (4), pp. 327–328.

KRISTIANSLUND, E. and KROSSHAUG, T., 2013. Comparison of drop jumps and sport-specific sidestep cutting: Implications for anterior cruciate ligament injury risk screening. *American Journal of Sports Medicine*. 41 (3), pp. 684–688.

KRISTIANSLUND, E., FAUL, O., BAHR, R., MYKLEBUST, G., and KROSSHAUG, T., 2014. Sidestep cutting technique and knee abduction loading: Implications for ACL prevention exercises. *British Journal of Sports Medicine*. 48 (9), pp. 779–783.

KROSSHAUG, T., STEFFEN, K., KRISTIANSLUND, E., NILSTAD, A., MOK, K.-M., MYKLEBUST, G., ANDERSEN, T.E., HOLME, I., ENGEBRETSEN, L., and BAHR, R., 2016. The Vertical Drop Jump Is a Poor Screening Test for ACL Injuries in Female Elite Soccer and Handball Players: A Prospective Cohort Study of 710 Athletes. *The American Journal of Sports Medicine*. 44 (4), pp. 874–883.

KUCERA, K.L., MARSHALL, S.W., KIRKENDALL, D.T., MARCHAK, P.M., and GARRETT, W.E., 2005. Injury history as a risk factor for incident injury in youth soccer. *British Journal of Sports Medicine*. 39 (7), pp. 462–466.

KYRITSIS, P., BAHR, R., LANDREAU, P., MILADI, R., and WITVROUW, E., 2016. Likelihood of ACL graft rupture: Not meeting six clinical discharge criteria before return to sport is associated with a four times greater risk of rupture. *British Journal of Sports Medicine*. 50 (15), pp. 946–951.

LANDRY, S.C., MCKEAN, K.A., HUBLEY-KOZEY, C.L., STANISH, W.D., and DELUZIO, K.J., 2007. Neuromuscular and lower limb biomechanical differences exist between male and female elite adolescent soccer players during an unanticipated run and crosscut maneuver. *American Journal of Sports Medicine*. 35 (11), pp. 1901–1911.

LE GALL, F., CARLING, C., and REILLY, T., 2008. Injuries in young elite female soccer players: an 8-season prospective study. *American Journal of Sports Medicine*. 36 (2), pp. 276–284.

LE GALL, F., CARLING, C., REILLY, T., VANDEWALLE, H., CHURCH, J., and ROCHCONGAR, P., 2006. Incidence of injuries in elite French youth soccer players: A 10-season study. *American Journal of Sports Medicine*. 34 (6), pp. 928–938.

LEE, J.W.Y., MOK, K.M., CHAN, H.C.K., YUNG, P.S.H., and CHAN, K.M., 2017. Eccentric hamstring strength deficit and poor hamstring-to-quadriceps ratio are risk factors for hamstring strain injury in football: A prospective study of 146 professional players. *Journal of Science and Medicine in Sport*. In press.

LEPLEY, L.K., 2015. Deficits in Quadriceps Strength and Patient-Oriented Outcomes at Return to Activity After ACL Reconstruction: A Review of the Current Literature. *Sports Health*. 7 (3), pp. 231–238.

LEPPÄNEN, M., PASANEN, K., KROSSHAUG, T., KANNUS, P., VASANKARI, T., KUJALA, U.M., BAHR, R., PERTTUNEN, J., and PARKKARI, J., 2017. Sagittal Plane Hip, Knee, and Ankle Biomechanics and the Risk of Anterior Cruciate Ligament Injury: A Prospective Study. *Orthopaedic Journal of Sports Medicine*. 5 (12).

LI, G., RUDY, T.W., SAKANE, M., KANAMORI, A., MA, C.B., and WOO, S.L.Y., 1999. The importance of quadriceps and hamstring muscle loading on knee kinematics and in-situ forces in the ACL. *Journal of Biomechanics*. 32 (4), pp. 395–400.

LOGERSTEDT, D., GRINDEM, H., LYNCH, A., EITZEN, I., ENGEBRETSEN, L., RISBERG, M.A., AXE, M.J., and SNYDER-MACKLER, L., 2012. Single-legged hop tests as predictors of self-reported knee function after anterior cruciate ligament reconstruction: The Delaware-Oslo ACL cohort study. *American Journal of Sports Medicine*. 40 (10), pp. 2348–2356.

MAFFIULETTI, N.A., BIZZINI, M., DESBROSSES, K., BABAULT, N., and MUNZINGER, U., 2007. Reliability of knee extension and flexion measurements using the Con-Trex isokinetic dynamometer. *Clinical Physiology and Functional Imaging*. 27 (6), pp. 346–353.

MALINZAK, R.A., COLBY, S.M., KIRKENDALL, D.T., YU, B., and GARRETT, W.E., 2001. A comparison of knee joint motion patterns between men and women in selected athletic tasks. *Clinical Biomechanics*. 16 (5), pp. 438–445.

MANDELBAUM, B.R., SILVERS, H.J., WATANABE, D.S., KNARR, J.F., THOMAS, S.D., GRIFFIN, L.Y., KIRKENDALL, D.T., and GARRETT, W., 2005. Effectiveness of a neuromuscular and proprioceptive training program in preventing anterior cruciate ligament injuries in female athletes: 2-Year follow-up. *American Journal of Sports Medicine*. 33 (7), pp. 1003–1010.

MANSON, S.A., BRUGHELLI, M., and HARRIS, N.K., 2014. Physiological characteristics of international female soccer players. *Journal of Strength & Conditioning Research*. 28 (2), pp. 308–318.

MARCHANT, D.C. and GREIG, M., 2017. Attentional focusing instructions influence quadriceps activity characteristics but not force production during isokinetic knee extensions. *Human Movement Science*. 52, pp. 67–73.

MCCALL, A., CARLING, C., DAVISON, M., NEDELEC, M., LE GALL, F., BERTHOIN, S., and DUPONT, G., 2015. Injury risk factors, screening tests and preventative strategies: A systematic review of the evidence that underpins the perceptions and practices of 44 football (soccer) teams from various premier leagues. *British Journal of Sports Medicine*. 49(9), pp. 583-590.

MCHORNEY, C.A. and TARLOV, A.R., 1995. Individual-patient monitoring in clinical practice: are available health status surveys adequate? *Quality of Life Research*. 4 (4), pp. 293–307.

MCLEAN, S.G., 2008. The ACL injury enigma: We can't prevent what we don't understand. *Journal of Athletic Training*. 43(5), pp. 538-540

MEINERZ, C.M., MALLOY, P., GEISER, C.F., and KIPP, K., 2015. Anticipatory effects on lower extremity neuromechanics during a cutting task. *Journal of Athletic Training*. 50 (9), pp. 905–913.

MJØLSNES, R., ARNASON, A., ØSTHAGEN, T., RAASTAD, T., and BAHR, R., 2004. A 10-week randomized trial comparing eccentric vs. concentric hamstring strength training in well-trained soccer players. *Scandinavian Journal of Medicine and Science in Sports*. 14 (5), pp. 311–317.

MOK, K.M., BAHR, R., and KROSSHAUG, T., 2017. Reliability of lower limb biomechanics in two sport-specific sidestep cutting tasks. *Sports Biomechanics*. pp. 1–11.

MORGAN, D.L. and PROSKE, U., 2004. Popping sarcomere hypothesis explains stretch-induced muscle damage. In: *Clinical and Experimental Pharmacology and Physiology*. pp. 541–545.

MORGAN, D.L., 1990. New insights into the behavior of muscle during active lengthening. *Biophysical Journal*. 57 (2), pp. 209–221.

MYER, G.D., FORD, K.R., and HEWETT, T.E., 2004. Rationale and clinical techniques for anterior cruciate ligament injury prevention among female athletes. *Journal of Athletic Training*. 39 (4), pp. 352–364.

MYER, G.D., CHU, D.A., BRENT, J.L., and HEWETT, T.E., 2008. Trunk and Hip Control Neuromuscular Training for the Prevention of Knee Joint Injury. *Clinics in Sports Medicine*. 27(3), pp. 425-448

MYER, G.D., FAIGENBAUM, A.D., FORD, K.R., BEST, T.M., BERGERON, M.F., and HEWETT, T.E., 2011. When to initiate integrative neuromuscular training to reduce sports-related injuries and enhance health in youth? *Current Sports Medicine Reports*. 10(3), pp.155-66

MYER, G.D., FORD, K.R., BRENT, J.L., and HEWETT, T.E., 2007. Differential neuromuscular training effects onACL injury risk factors in"high-risk" versus ‘low-risk’ athletes. *BMC Musculoskeletal Disorders*. 8.

MYER, G.D., FORD, K.R., DI STASI, S.L., BARBER FOSS, K.D., MICHELI, L.J., and HEWETT, T.E., 2015. High knee abduction moments are common risk factors for patellofemoral pain (PFP) and anterior cruciate ligament (ACL) injury in girls: Is PFP itself a predictor for subsequent ACL injury? *British Journal of Sports Medicine*. 49 (2), pp. 118–122.

MYER, G.D., FORD, K.R., FOSS, K.D.B., LIU, C., NICK, T.G., and HEWETT, T.E., 2009. The Relationship of Hamstrings and Quadriceps Strength to Anterior Cruciate Ligament Injury in Female Athletes. *Clinical Journal of Sport Medicine*. 19, pp. 3–8.

MYER, G.D., FORD, K.R., MCLEAN, S.G., and HEWETT, T.E., 2006. The effects of plyometric versus dynamic stabilization and balance training on lower extremity biomechanics. *American Journal of Sports Medicine*. 34 (3), pp. 445–455.

NEDERGAARD, N.J., KERSTING, U., and LAKE, M., 2014. Using accelerometry to quantify deceleration during a high-intensity soccer turning manoeuvre. *Journal of Sports Sciences*. 32 (20), pp. 1897–1905.

NILSTAD, A., ANDERSEN, T.E., BAHR, R., HOLME, I., and STEFFEN, K., 2014. Risk Factors for Lower Extremity Injuries in Elite Female Soccer Players. *The American Journal of Sports Medicine*. 42 (4), pp. 940–948.

NORCROSS, M.F., LEWEK, M.D., PADUA, D.A., SHULTZ, S.J., WEINHOLD, P.S., and BLACKBURN, J.T., 2013. Lower extremity energy absorption and biomechanics during landing, part I: Sagittal-plane energy absorption analyses. *Journal of Athletic Training*. 48 (6), pp. 748–756.

OLSEN, O.-E., MYKLEBUST, G., ENGEBRETSEN, L., and BAHR, R., 2004. Injury mechanisms for anterior cruciate ligament injuries in team handball: a systematic video analysis. *American Journal of Sports Medicine*. 32 (4), pp. 1002–1012.

OPAR, D.A., WILLIAMS, M.D., TIMMINS, R.G., HICKEY, J., DUHIG, S.J., and SHIELD, A.J., 2015. Eccentric hamstring strength and hamstring injury risk in Australian footballers. *Medicine and Science in Sports and Exercise*. 47 (4), pp. 857–865.

ORTIZ, A., OLSON, S., TRUDELLE-JACKSON, E., ROSARIO, M., and VENEGAS, H.L., 2011. Landing Mechanics During Side Hopping and Crossover Hopping Maneuvers in Noninjured Women and Women With Anterior Cruciate Ligament Reconstruction. *The Journal of Injury, Function and Rehabilitation*. 3 (1), pp. 13–20.

PAGE, R.M., MARRIN, K., BROGDEN, C.M., and GREIG, M., 2017. The physical response to a simulated period of soccer-specific fixture congestion. *Journal of Strength and Conditioning Research*. p. 1.

PAPPAS, E., HAGINS, M., SHEIKHZADEH, A., NORDIN, M., and ROSE, D., 2007. Biomechanical differences between unilateral and bilateral landings from a jump: Gender differences. *Clinical Journal of Sport Medicine*. 17 (4), pp. 263–268.

PAPPAS, E., SHIYKO, M.P., FORD, K.R., MYER, G.D., and HEWETT, T.E., 2016. Biomechanical deficit profiles associated with acl injury risk in female athletes. *Medicine and Science in Sports and Exercise*. 48 (1), pp. 107–113.

PADUA, D., A., 2014. The Jump ACL Study - Drop jump task can predict ACL injuries in US military cadets. IOC World Conference Prevention of Injury & Illness in Sport; 2014; Monaco.

PETERSEN, J., THORBORG, K., NIELSEN, M.B., BUDTZ-JØRGENSEN, E., and HÖLMICH, P., 2011. Preventive effect of eccentric training on acute hamstring injuries in Men's soccer: A cluster-randomized controlled trial. *American Journal of Sports Medicine*. 39 (11), pp. 2296–2303.

PODRAZA, J.T. and WHITE, S.C., 2010. Effect of knee flexion angle on ground reaction forces, knee moments and muscle co-contraction during an impact-like deceleration landing: Implications for the non-contact mechanism of ACL injury. *Knee*. 17 (4), pp. 291–295.

POTTER, D., SZYMIALOWICZ, R., MARTIN, T., DIONE, D., FEINN, R., WALLACE, D., and GARBALOSA, J.C., 2014. Sidestep and crossover lower limb kinematics during a prolonged sport-like agility test. *International Journal of Sports Physical Therapy*. 9 (5), pp. 617–627.

PRICE, M.J., TUCA, M., CORDASCO, F.A., and GREEN, D.W., 2017. Nonmodifiable risk factors for anterior cruciate ligament injury. *Current Opinion in Pediatrics*. 29(1), pp. 55-64

PRICE, R.J., HAWKINS, R.D., HULSE, M.A., and HODSON, A., 2004. The Football Association medical research programme: An audit of injuries in academy youth football. *British Journal of Sports Medicine*. 38 (4), pp. 466–471.

QUATMAN, C.E., QUATMAN-YATES, C.C., and HEWETT, T.E., 2010. A ‘plane’ explanation of anterior cruciate ligament injury mechanisms: a systematic review. *Sports Medicine*. 40 (9), pp. 729–746.

RAE, D.E., STEPHENSON, K.J., and RODEN, L.C., 2015. Factors to consider when assessing diurnal variation in sports performance: the influence of chronotype and habitual training time-of-day. *European Journal of Applied Physiology*. 115 (6), pp. 1339–1349.

RENSHAW, A. and GOODWIN, P.C., 2016. Injury incidence in a Premier League youth soccer academy using the consensus statement: a prospective cohort study. *BMJ Open Sport & Exercise Medicine*. 2 (1), p. e000132.

RENSTROM, P., LJUNGQVIST, A., ARENDT, E., BEYNNON, B., FUKUBAYASHI, T., GARRETT, W., GEORGOULIS, T., HEWETT, T.E., JOHNSON, R., KROSSHAUG, T., MANDELBAUM, B., MICHELI, L., MYKLEBUST, G., ROOS, E., ROOS, H., SCHAMASCH, P., SHULTZ, S., WERNER, S., WOJTYS, E., and ENGEBRETSEN, L., 2008. Non-contact ACL injuries in female athletes: An International Olympic Committee current concepts statement. *Sport en Geneeskunde*. 41 (3), pp. 14–27.

ROCHA VIEIRA, D.S., BARIL, J., RICHARD, R., PERRAULT, H., BOURBEAU, J., and TAIVASSALO, T., 2011. Eccentric cycle exercise in severe COPD: Feasibility of application. *COPD: Journal of Chronic Obstructive Pulmonary Disease*. 8 (4), pp. 270–274.

RUDOLPH, K.S., AXE, M.J., and SNYDER-MACKLER, L., 2000. Dynamic stability after ACL injury: Who can hop? *Knee Surgery, Sports Traumatology, Arthroscopy*. 8 (5), pp. 262–269.

RUSSELL, K.A., PALMIERI, R.M., ZINDER, S.M., and INGERSOLL, C.D., 2006. Sex differences in valgus knee angle during a single-leg drop jump. *Journal of Athletic Training*. 41 (2), pp. 166–171.

SANKEY, S.P., RAJA AZIDIN, R.M.F., ROBINSON, M.A., MALFAIT, B., DESCHAMPS, K., VERSCHUEREN, S., STAES, F., and VANRENTERGHEM, J., 2015. How reliable are knee kinematics and kinetics during side-cutting manoeuvres? *Gait and Posture*. 41 (4), pp. 905–911.

SCHMITT, L.C., PATERNO, M. V., FORD, K.R., MYER, G.D., and HEWETT, T.E., 2015. Strength asymmetry and landing mechanics at return to sport after anterior cruciate ligament reconstruction. *Medicine and Science in Sports and Exercise*. 47 (7), pp. 1426–1434.

SEERING, W.P., PIZIALI, R.L., NAGEL, D.A., and SCHURMAN, D.J., 1980. The function of the primary ligaments of the knee in varus-valgus and axial rotation. *Journal of Biomechanics*. 13 (9), pp. 785–794.

SHARIR, R., RAFEEUDDIN, R., STAES, F., DINGENEN, B., GEORGE, K., VANRENTERGHEM, J., and ROBINSON, M.A., 2016. Mapping current research trends on anterior cruciate ligament injury risk against the existing evidence: In vivo biomechanical risk factors. *Clinical Biomechanics*. 37, pp. 34-43.

SHIMOKOCHI, Y., LEE, S.Y., SHULTZ, S.J., and SCHMITZ, R.J., 2009. The relationships among sagittal-plane lower extremity moments: Implications for landing strategy in anterior cruciate ligament injury prevention. *Journal of Athletic Training*. 44 (1), pp. 33–38.

SIGWARD, S. and POWERS, C.M., 2006. The influence of experience on knee mechanics during side-step cutting in females. *Clinical Biomechanics*. 21 (7), pp. 740–747.

SIGWARD, S.M., CESAR, G.M., and HAVENS, K.L., 2014. Predictors of Frontal Plane Knee Moments During Side-Step Cutting to 45 and 110 Degrees in Men and Women. *Clinical Journal of Sport Medicine*. p. 1.

SMALL, K., MCNAUGHTON, L., GREIG, M., and LOVELL, R., 2010. The effects of multidirectional soccer-specific fatigue on markers of hamstring injury risk. *Journal of Science and Medicine in Sport*. 13 (1), pp. 120–125.

SÖDERMAN, K., PIETILÄ, T., ALFREDSON, H., and WERNER, S., 2002. Anterior cruciate ligament injuries in young females playing soccer at senior levels. *Scandinavian Journal of Medicine & Science in Sports*. 12, pp. 65–68.

STAPLETON, T.R., WALDROP, J.I., RUDER, C.R., PARRISH, T. a, and KUIVILA, T.E., 1998. Graft fixation strength with arthroscopic anterior cruciate ligament reconstruction. Two-incision rear entry technique compared with one-incision technique. *The American Journal of Sports Medicine*. 26 (3), pp. 442–5.

STARK, T., WALKER, B., PHILLIPS, J.K., FEJER, R., and BECK, R., 2011. Hand-held dynamometry correlation with the gold standard isokinetic dynamometry: A systematic review. *PM and R*. 3(5), pp. 472-479

STUBBE, J.H., VAN BEIJSTERVELDT, A.M.M.C., VAN DER KNAAP, S., STEGE, J., VERHAGEN, E.A., VAN MECHELEN, W., and BACKX, F.J.G., 2015. Injuries in professional male soccer players in the Netherlands: A prospective cohort study. *Journal of Athletic Training*. 50 (2), pp. 211–216.

SUGIMOTO, D., MYER, G.D., BARBER FOSS, K.D., PEPIN, M.J., MICHELI, L.J., and HEWETT, T.E., 2016. Critical components of neuromuscular training to reduce ACL injury risk in female athletes: meta-regression analysis. *British Journal of Sports Medicine*. 50 (20), pp. 1259–1266.

SUGIMOTO, D., MYER, G.D., MCKEON, J.M., and HEWETT, T.E., 2012. Evaluation of the effectiveness of neuromuscular training to reduce anterior cruciate ligament injury in female athletes: a critical review of relative risk reduction and numbers-needed-to-treat analyses. *British Journal of Sports Medicine*. 46(14), pp. 979-988.

TAYLOR, J.B., WRIGHT, A.A., DISCHIAVI, S.L., TOWNSEND, M.A., and MARMON, A.R., 2017. Activity Demands During Multi-Directional Team Sports: A Systematic Review. *Sports Medicine*. 47(12), pp. 2533-2551

THELEN, D.G., CHUMANOV, E.S., HOERTH, D.M., BEST, T.M., SWANSON, S.C., LI, L., YOUNG, M., and HEIDERSCHEIT, B.C., 2005. Hamstring muscle kinematics during treadmill sprinting. *Medicine and Science in Sports and Exercise*. 37 (1), pp. 108–114.

THOMAS, A.C., VILLWOCK, M., WOJTYS, E.M., and PALMIERI-SMITH, R.M., 2013. Lower extremity muscle strength after anterior cruciate ligament injury and reconstruction. *Journal of Athletic Training*. 48 (5), pp. 610–620.

TOONSTRA, J. and MATTACOLA, C.G., 2013. Test–Retest Reliability and Validity of Isometric Knee-Flexion and -Extension Measurement Using 3 Methods of Assessing Muscle Strength. *Journal of Sport Rehabilitation*.

VAN BEIJSTERVELDT, A.M.C., STUBBE, J.H., SCHMIKLI, S.L., VAN DE PORT, I.G.L., and BACKX, F.J.G., 2015. Differences in injury risk and characteristics between Dutch amateur and professional soccer players. *Journal of Science and Medicine in Sport*. 18 (2), pp. 145–149.

VAN DER HORST, N., SMITS, D.W., PETERSEN, J., GOEDHART, E.A., and BACKX, F.J.G., 2015. The Preventive Effect of the Nordic Hamstring Exercise on Hamstring Injuries in Amateur Soccer Players: A Randomized Controlled Trial. *American Journal of Sports Medicine*. 43 (6), pp. 1316–1323.

VAN DER SLUIS, A., ELFERINK-GEMSER, M.T., BRINK, M.S., and VISSCHER, C., 2015. Importance of peak height velocity timing in terms of injuries in talented soccer players. *International Journal of Sports Medicine*. 36 (4), pp. 327–332.

VAN DER SLUIS, A., ELFERINK-GEMSER, M.T., COELHO-E-SILVA, M.J., NIJBOER, J.A., BRINK, M.S., and VISSCHER, C., 2014. Sport injuries aligned to Peak Height Velocity in talented pubertal soccer players. *International Journal of Sports Medicine*. 35 (4), pp. 351–355.

VAN DYK, N., BAHR, R., BURNETT, A.F., WHITELEY, R., BAKKEN, A., MOSLER, A., FAROOQ, A., and WITVROUW, E., 2017. A comprehensive strength testing protocol offers no clinical value in predicting risk of hamstring injury: A prospective cohort study of 413 professional football players. *British Journal of Sports Medicine*. 51 (23), pp. 1695–1702.

VAN DYK, N., BAHR, R., WHITELEY, R., TOL, J.L., KUMAR, B.D., HAMILTON, B., FAROOQ, A., and WITVROUW, E., 2016. Hamstring and Quadriceps Isokinetic Strength Deficits Are Weak Risk Factors for Hamstring Strain Injuries. *American Journal of Sports Medicine*. 44 (7), pp. 1789–1795.

VAN MECHELEN, W., HLOBIL, H., and KEMPER, H.C.G., 1992. Incidence, Severity, Aetiology and Prevention of Sports Injuries: A Review of Concepts. *Sports Medicine: An International Journal of Applied Medicine and Science in Sport and Exercise*. 14(2), pp. 82-99.

VANRENTERGHEM, J., VENABLES, E., PATAKY, T., and ROBINSON, M.A., 2012. The effect of running speed on knee mechanical loading in females during side cutting. *Journal of Biomechanics*. 45 (14), pp. 2444–2449.

VARLEY, M.C. and AUGHEY, R.J., 2013. Acceleration profiles in elite Australian soccer. *International Journal of Sports Medicine*. 34 (1), pp. 34–39.

WALDÉN, M., HÄGGLUND, M., MAGNUSSON, H., and EKSTRAND, J., 2016. ACL injuries in men's professional football: A 15-year prospective study on time trends and return-to-play rates reveals only 65% of players still play at the top level 3 years after ACL rupture. *British Journal of Sports Medicine*. 50 (12), pp. 744–750.

WALDÉN, M., KROSSHAUG, T., BJØRNEBOE, J., ANDERSEN, T.E., FAUL, O., and HÄGGLUND, M., 2015. Three distinct mechanisms predominate in noncontact anterior cruciate ligament injuries in male professional football players: A systematic video analysis of 39 cases. *British Journal of Sports Medicine*. 49 (22), pp. 1452–1460.

WANG, L.I., 2011. The lower extremity biomechanics of single- and double-leg stop-jump tasks. *Journal of Sports Science and Medicine*. 10 (1), pp. 151–156.

WOODS, C., 2004. The Football Association Medical Research Programme: an audit of injuries in professional football--analysis of hamstring injuries. *British Journal of Sports Medicine*. 38 (1), pp. 36–41.

WRIGLEY, R., DRUST, B., STRATTON, G., SCOTT, M., and GREGSON, W., 2012. Quantification of the typical weekly in-season training load in elite junior soccer players. *Journal of Sports Sciences*. 30 (15), pp. 1573–1580.

YANAGAWA, T., SHELBURNE, K., SERPAS, F., and PANDY, M., 2002. Effect of hamstrings muscle action on stability of the ACL-deficient knee in isokinetic extension exercise. *Clinical Biomechanics*. 17 (9–10), pp. 705–712.

YDE, J. and NIELSEN, a B., 1990. Sports injuries in adolescents' ball games: soccer, handball and basketball. *British Journal of Sports Medicine*. 24 (1), pp. 51–54.

YOM, J.P., OWENS, T., ARNETT, S., BEEBE, J., and SON, V., 2018. The effects of an unanticipated side-cut on lower extremity kinematics and ground reaction forces during a drop landing. *Sports Biomechanics*. pp. 1–12.

ZVIJAC, J.E., TORISCELLI, T.A., MERRICK, W.S., PAPP, D.F., and KIEBZAK, G.M., 2014. Isokinetic concentric quadriceps and hamstring normative data for elite collegiate American football players participating in the NFL scouting combine. *Journal of Strength and Conditioning Research*. 28 (4), pp. 875–883.